2015

The Path to Success: Failures in Real Robots (FinE-R)

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FinE-R 2015

The Path to Success: Failures in rEal Robots

Main goals of the workshop

Along the history, there are many important discoveries that resulted from long trials and error processes (e.g. the electric light bulb from Edison) or from analysing 'failed' results (e.g. the Michelson-Morley experiment). In each case, the key contributor for the final success was the willingness to learn from previous mistakes and to share the gained experience with the research community.

The path to progress in the field of robotics is not free of failures and caveats. These failures provide valuable lessons and insights on future approaches by analysing errors and finding methods to avoid them. As such, the robotics community could benefit from the experience of those who had faced and overcome similar failures before.

The objective of this workshop is to provide a forum for researchers to share their personal experiences on their "failure to success" stories, to present what they have learnt, what others should avoid while experimenting in similar context, providing tips for better research practices and for creating more successful robots that meet people's expectations.

Topics of interest (but not limited to)

- Analysis of failures when participating in robotic challenges
- Design of robust human-computer interfaces for robots
- When failure is not an option: creating an outstanding robot from HW to SW
- The search for errors: benchmarking and tools for testing robots
- Avoiding common but frequently seen errors when deploying robots for industrial or general public environments
- Advanced techniques for failure recovery and troubleshooting
- Matching the expectations and needs of industries and consumers with the current technology
- Alternatives to techniques and algorithms that are prone to fail
- The keys for successful research projects and proposals on robotics
- Analysis of failed results and projects when using smart algorithms, well-established techniques or brilliant designs

INVITED KEYNOTE SPEAKERS

Ryad Chellali

Nanjing Robotics Institute- CEECS
Nanjing Tech University, Nanjing, China

rchellali@njtech.edu.cn

Lessons Learned in Human Movements and Behavior Analysis

Human Robots Interactions (HRI) is a hybrid filed mixing many domains including engineering, physics, social sciences, neurosciences, etc. Accordingly, research in HRI combines exact models and experimental approaches towards developing interaction frameworks and friendly robots. The inherent heterogeneity leads in many cases to ill-posed problems with oversimplification on one side (the engineering side) and forced (thus inexact) models on the other side. Indeed and for the "R" part in HRI, measurements and procedures are known to be exact and objective. Models in these fields are enough known allowing quantitative accurate observations that can be measured repeatedly supporting the original models. In psychology and social sciences the situation is different: the object of studies, namely humans, is much less known. Scientists in these areas are lacking in terms of accurate models compared physicists and engineers. Indeed, humans can be seen as high dimension multivariate systems, with complex dynamics, preventing from having complete explanatory models. This leads to qualitative approaches, where only isolated aspects (and most of the time related indirectly to the object of investigations) are considered. This situation is even worst when experiments are performed in real life conditions. Indeed, to obtain realistic observations, experiments in real world are needed; unfortunately, the control of experimental conditions is almost impossible out of laboratories, leading to higher difficulty and complexity in analysis and understanding.

Through our previous works, we found out that one should consider carefully modelling human behaviour. In analysing human gestures for instance, our system used to work well in lab conditions but failed completely in real situations. We imposed a model that cannot handle the variability both intra-personal and inter-personal. Likewise, in studying relationships between body movements and human physiology, we found out a new phenomenon that was not considered in our original model. Our conclusion (which is obvious a posteriori) is that model driven approaches are useless in human behaviour analysis. Instead, data driven techniques (unsupervised, latent modelling, etc.) seem to be more effective. Indeed, in both previous cases we achieved better results by removing modelling constraints and by using statistical tools extracting weakly hypothesized regularity.

Short Bio

Ryad Chellali is a distinguished professor at Nanjing Tech University, Nanjing China since 2015. From 2005 to 2015, he was senior research scientist at the Italian Institute of Technology. He created and leaded the

Human Robots Mediated Interactions Group (2006-2011) and then joined the Department of Pattern Analysis and Computer Vision (PAVIS, 2011-2015). From 1995 to 2006, he was with Ecole des Mines de Nantes/CNRS (France), heading the automatic control chair. From 1993 to 1995 he was assistant professor at University of Paris. He served as Junior Researcher in 1992 at the French Institute of Transports (INRETS). He obtained his Ph.D. in Robotics from University of Paris in 1993 and his Dr. Sc from University of Nantes (France) in 2005. His main research interests include robotics, human-robot interactions, human behavior analysis (social signal processing and affective computing). Telepresence, virtual and augmented realities are also keywords of his activity.

Ryad Chellali co-authored more than 100 papers. In 2000 and 2005 the French Government awarded him for the creation of innovative technologies companies.

Laurence DeVillers

LIMSI-CNRS, Sorbonne University, France
laurence.devillers@limsi.fr

The communication accommodation of the machine to deal with errors in Human-Robot Spoken Interaction

Talk during social interactions naturally involves the exchange of propositional content but also and perhaps more importantly the expression of interpersonal relationships, as well as displays of emotion, affect, interest, etc. Such social interaction requires that the robot has the ability to detect, interpret the social language and represent some complex human social behaviour. Cognitive decisions will be used for reasoning on the strategy of the dialog and deciding social behaviours (humour, compassion, white lies, etc.) taking into account the user profile and contextual information. The research challenges also include the evaluation of such systems and the various metrics that could be used like the measure of social engagement with the user. Engagement in dialog with a machine is not only linked to the error rates. We argue that the communication accommodation theory is a promising paradigm to globally consider the errors in the convergence or divergence dimensions.

Short Bio

Laurence DeVillers is a Professor of Affective Computing at Paris-Sorbonne University and she leads a team of research on "Affective and Social Dimensions of Spoken Interactions" at the CNRS. Her current research addresses the problem of sensing and understanding human non-verbal interactive language and intentions. Her background is on machine learning, speech recognition, spoken dialog system and evaluation. She participates in BPI ROMEO2 project, which has the main goal of building a social humanoid robot for elderly people. She leads the European CHIST-ERA project JOKER: JOKe and Empathy of a Robot. She is member of the working group on the ethics of the research in robotics (CERNA). She is also heading the "Human-machine co-evolution" research group at the Numerical Society Institute (France). She has (co-) authored more than 140 publications. She is a member of AAAC (board), IEEE, ACL, ISCA, WACAI and AFCP. She is also involved in the Eurobotics Topic Groups: "Natural Interaction with Social Robots" and "Socially intelligent robots". (Video-demo[1]).

Short institution presentation

The Computer Sciences Laboratory for Mechanics and Engineering Sciences (LIMSI) is one of France's largest research laboratories of the CNRS working on language technologies. The team on "Affective and Social Dimensions of Spoken Interactions" (Head: L. Devillers) is working on affective computing and robotics applications[2].

[1] https://www.youtube.com/watch?v=p1ID-gvUnWs
[2] https://www.limsi.fr/en/research/tlp/topics/topic2

ORGANIZING COMMITTEE

Luis Fernando D'Haro
Chair

*SERC Robotics Program, A*STAR*
Institute for Infocomm Research, Singapore

luisdhe@i2r.a-star.edu.sg

Andreea Ioana Niculescu
Co-Chair

*SERC Robotics Program, A*STAR*
Institute for Infocomm Research, Singapore

Aravindkumar Vijayalingam
Technical Program

TUM CREATE, Singapore

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- Rafael E. Banchs, Human Language Technologies - A*STAR, Singapore
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- Gamini Dissanayake, University of Technology, Sydney (Australia)
- Ismael García-Varea, University of Castilla-La Mancha, Spain
- Marco Antonio Gutierrez Giraldo, Robolab, Universidad de extremadura, Spain
- Martin Hägele, Head of Department Robotics and Assistive Systems, Fraunhofer IPA, Germany
- Haizhou Li, Human Language Technologies - A*STAR, Singapore
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- Jose Moreno, University of Extremadura, Spain
- Omar Mubin, University of Western Sydney, HCI & Robotics
- Suraj Nair, TUM, Germany
- Andreea Ioana Niculescu, SERC Robotics Program - A*STAR, Singapore
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- Aravindkumar Vijayalingam, TUM CREATE, Singapore
- Erik Wilhelm, Singapore University of Technology and Design, Singapore
- Martin Wojtczyk, Baylabs, California (USA)
- Thilo Zimmermann, GPS Stuttgart, Germany

SUPPORTING ORGANIZATIONS

LIST OF ACCEPTED CONTRIBUTIONS

SCHEDULE

Session	Title
8:45 – 9:00	Opening Ceremony
9:00 – 10:00	Keynote: Lessons Learned in Human Movements and Behavior Analysis Ryad Chellali (Nanjing Robotics Institute- CEECS, Nanjing Tech University, Nanjing, China)
10:00 – 10:30	**Coffee Break**
10:30 – 10:50	*"Intelligence Level Performance Standards Research for Autonomous Vehicles"* - Roger Bostelman, Tsai Hong, and Elena Messina.
10:50 – 11:10	*"Lessons from the Design and Testing of a Novel Spring Powered Passive Robot Joint"* - Joel Stephen Short, Aun Neow Poo, Chow Yin Lai, Pey Yuen Tao, and Marcelo H Ang Jr.
11:10 – 11:30	*"Improvements and considerations related to human-robot interaction in the design of a new version of the robotic head Muecas"* - Felipe Cid Burgos, Pedro Núñez Trujillo and Luis J. Manso.
11:30 – 11:50	*"Adapting Low-Cost Platforms for Robotics Research"* - Thommen Karimpanal George, Mohammadreza Chamanbaz, Abhishek Gupta, Wen Lizheng, Timothy Jeruzalski, and Erik Wilhelm.
11:50 – 12:10	*"Using Autonomous Robots to Diagnose Wireless Connectivity"* - Richard Wang, Manuela Veloso, and Srinivasan Seshan
12:10 – 14:10	**Lunch time**
14:10 – 15:10	Keynote: The communication accommodation of the machine to deal with errors in Human-Robot Spoken Interaction Laurence DeVillers (LIMSI-CNRS, Sorbonne University, France)
15:10 – 15:30	*"Toward Soft, Robust Robots for Children with Autism Spectrum Disorder"* - Hong Tuan Teo, and John-John Cabibihan.
15:30 – 16:00	**Coffee Break**
16:00 – 16:20	*"Gualzru's path to the Advertisement World"* - Fernando Fernández, Moisés Martínez, Ismael García-Varea, Jesús Martínez-Gómez, Jose Pérez-Lorenzo, Raquel Viciana, Pablo Bustos, Luis Manso, Luis Calderita, Marco Gutiérrez, Pedro Núñez, Antonio Bandera, Adrián Romero-Garcés, Juan Bandera and Rebeca Marfil.
16:20 – 16:40	*"Design, Simulation and Implementation of a 3-PUU Parallel Mechanism for a*

	Macro/mini Manipulator" - Zheng Ma, Aun-Neow Poo, Marcelo Ang, Geok-Soon Hong and Feng Huo.
16:40 – 17:00	*"Skill-based Exception Handling and Error Recovery for Collaborative Industrial Robots"*- Anders Billesø Beck, Anders Due Schwartz, Andreas R. Fugl, Martin Naumann, and Björn Kahl.
17:00 – 17:10	Closing Ceremony

The path to success: Failures in rEal Robots (FinE-R)

Luis Fernando D'Haro[1], *Member, IEEE*, Andreea I. Niculescu[1], Aravindkumar Vijayalingam[2], Marco A. Gutierrez[1,3] *Member, IEEE*, Suraj Nair[2], Rafael E. Banchs[1], *Member IEEE*

***Abstract*— This paper presents our motivation for organizing the FinE-R workshop at IROS 2015, as well as a summary of all accepted papers. The main workshop goal is to provide an open exchange forum to the robotic community where participants can share their personal "failure to success" stories. We believe that such exchanges are of tremendous importance for the community as they provide a rich source of knowledge on how to avoid future mistakes with possible high impact. On the other hand, the papers accepted in the workshop give a good overview of different types of errors encountered in the robotic fields. Through deep analysis and clear description of failures, the authors of these papers contribute to a learning process by extracting positive experiences and conclusions from negative results leading ultimately to success.**

Keywords: Workshop goals, summary of accepted papers, failure analysis.

I. INTRODUCTION

Along the history there have been many important discoveries that resulted from long trials and error processes, like the ones done for the creation of the electric light bulb by Tomas A. Edison [1] (who is believed to have made thousands of experiments before successfully creating the incandescent lamp). Similarly, other important discoveries came out from analyzing 'failed' results as, for instance, the famous Michelson-Morley experiment in the late 1880's, designed to enhance the accuracy of the prevalent Aether theory. In this case, their efforts to advance the theory led to a continual rejection of their research hypotheses. However, their null results were published in [2] and later played an important role in inspiring new experiments and paradigms, like the special theory of relativity proposed by Albert Einstein in 1905. In each case, the key point for the final success and contribution to the science was the willingness of the researchers to learn from previous mistakes and to share the gained experience with the scientific community.

As many other sciences, the path to progress in the field of robotics is not free of failures and caveats. These failures provide valuable lessons and insights on future approaches by analyzing errors and finding methods to avoid them. As such, the robotics community could benefit from the experience of those who had faced and overcome similar failures before.

The objective of this workshop is then to provide an international forum for researchers in robotics and its related fields, where they can share their personal experiences on their "failure to success" stories, to present what they have learnt, what others should avoid while experimenting in similar context, and providing tips for better research practices and for creating more successful robots that meet people's expectations.

II. MOTIVATION FOR THE WORKSHOP

Nowadays, in the scientific community only successful theories and positive results have a chance of being regarded as true, and then published in prestigious publications, discarding odd and unexpected findings. However, the success of these theories does not warrant that they are truth neither prove their adequacy to realism. Unfortunately, the current scientific publishing system privileges "successful" results as it is expected that their research findings will be in alignment with well-established literature or with expected outcomes. However, as pointed by [3], research is a "voyage of discovery", which is subject to unpredictability and fallibility, therefore science evolves according to testability, which might result in refutations or confirmations, as well on the absence of anticipated correlations or in failed results, but in any case, it should be clear that both kind of results contribute to the advance of the science.

However, ignoring the huge amount of information that negative results can provide (which, according to [4], are statistically more trustworthy than positive data) is troublesome. Firstly, because by doing so, an important bias in the scientific publications is created since only certain pieces of information are provided. Regrettably, this tendency is yearly increased as pointed by [5], whom after analyzing over 4,600 papers published in different disciplines between 1990 and 2007 found that the proportion of published negative results dropped from 30% to 14% between 1990 and 2007, and with significant differences between disciplines and countries. Secondly, this tendency of omitting information can cause a huge waste of time and resources, as other scientists considering similar questions may perform the same experiments; besides, this can also delay the development of new ideas inspired on the 'unsuccessful' results. Finally, as pointed by [6], this problem is increased by the misconception that publishing negative results might harm scientists' reputations or, furthermore, it might give the perception that a project was poorly designed and the researchers were either

[1] Luis Fernando D'Haro, Andreea I. Niculescu and Rafael Banchs work at the Human Language Techonology Group in the Institute for Infocomm Research (I2R - A*STAR). 1 Fusionopolis Way, #21-01 Connexis (South Tower), Singapore 138632. (emails: {luisdhe, aandrea-n, rembanchs}@i2r.a-star.edu.sg).

[2] Aravindkumar Vijayalingam and Suraj Nair work at TUM-Create, 1 Create Way, 8th Floor, Singapore 138602. (emails: {aravind.v, suraj.nair}@tum-create.edu.sg)

[3] Marco Antonio Gutierrez is PhD student at the Robotics Laboratory (Robolab), Computer and Communication Technology Dept in the University of Extremadura, Spain. Polytechnic School, University of Extremadura Avda. de la Universidad s/n 10003 Cáceres-Spain. (email: marcog@unex.es). The author conducted this work as part of his A*STAR Research Attachment Programme (ARAP) at the Human Language Technology Department of Institute for Infocomm Research, Singapore.

unknowledgeable about the subject or incapable of tailoring more robust research hypotheses. To make things worse, some scientists will not report negative results just to avoid their papers to be rejected by the peer-reviewers, who could give priority to other studies with "successful" results or that follow a more popular theory or approach.

Fortunately, the scientific community is becoming aware that negative results are not meaningless and that there is a potential value in sharing also negative results and discussing the lessons learnt after analyzing the failures, as well as in explaining what were the keys to avoid problems and achieve successful results. Some examples of this tendency can be seem in the New Negatives in Plant journal[4] that according to their scope is "an open access, peer reviewed, online journal that publishes hypothesis-driven, scientifically sound studies describing unexpected, controversial, dissenting, and/or null (negative) results in basic plant sciences. The journal also consider studies that validate controversial results or results that cannot reproduce previously published data", or in the new approach supported by the Wealth Health Organization (WHO)[5] that has a new policy of publishing, in their peer reviewed journal, results of clinical trials that include also negative findings.

Following such examples and taking into account that the scientist community working in the robotics field can also benefit of following a similar approach, we decided to propose FinE-R (Failure in Real Robots), a workshop in the context of IROS[6] (IEEE/RSJ International Conference on Intelligent Robots and Systems) conference. For this, we decided not only to focus on presenting the negative results obtained while working on real robots, but also on how the researchers were able to extract meaningful lessons from their failures and what kind of solutions they proposed to finally overcome their problems. Then, we made the FinE-R's call for papers targeting at the following topics:

- Analysis of failures when participating in robotic challenges.
- Design of robust human-computer interfaces for robots.
- Description of problems and solutions faced when failure is not an option, therefore there is the need of creating an outstanding robot from hardware to software.
- Description of benchmarking and tools for testing and creating robust robots.
- Description of techniques to avoid common but frequently seen errors when deploying robots for industrial or general public environments.
- Description of advanced techniques for failure recovery and troubleshooting.
- Matching the expectations and needs of industries and consumers with the current technology.

[4] http://www.journals.elsevier.com/new-negatives-in-plant-science
[5] http://www.who.int/ictrp/results/reporting/en/
[6] http://www.iros2015.org

- Description of alternatives to techniques and algorithms that are prone to fail.
- Presentation of keys for successful research projects and proposals on robotics.
- Analysis of failed results and projects when using smart algorithms, well-established techniques or brilliant designs.

These proposed topics not only were in line with the idea of learning from failures, that is central to our workshop, but also allowed to differentiate FinE-R from other workshops that are mainly centered on specific and vertical topics or areas of research. With FinE-R we aim at providing a space for sharing practices and experiences of robot design and construction across multiple disciplines, therefore making the workshop more interesting and open to a wider audience.

Finally, it is worth mentioning that it was gratifying for us to read comments from reviewers of the Workshop proposal about the appropriateness and timelines of an initiative such as FinE-R. Some examples of these are:

"This is a very interesting proposal as learning from failure in real-world applications is an important and essential capability for robots. This is not a topic not well addressed so far. It is very good to see a group of people discussing this"

"This workshop will provide such a unique opportunity that we can learn from not only our own failure but also others. We surely need such a workshop. Topics cover wide ranges. Speakers are from well-known organizations. Suggest leaving more time for discussions."

III. Summary of Contributions

In this section we summarize the accepted contributions to the first edition of FinE-R. All submissions went through a single blind review process. In average, all papers received three reviews.

A. Skill-based Exception Handling and Error Recovery for Collaborative Industrial Robots

Written by Billesø et al [7], this paper discusses the problem of error handling and recovery in the context of open human workspaces. The authors propose a skill-based exception handling and error recovery approach that allows non-robot expert users to operate a robotic system in open environment where other human co-workers are present. The paper presents the skill-based execution model and describes the situation assessment module which learns and monitors the skill execution. Further, the authors show in details how their exception handler model based on a hierarchical four layered Bayesian network works. Non-expert users can accept or reject a solution of an error handling strategy using a simple GUI. The user preference is learned by the system for future re-use.

B. Using Autonomous Robots to Diagnose Wireless Connectivity

This paper, written by Wang et al [8], presents a method/system for diagnosis of wireless connectivity issues through the use of autonomous robots within the author's building infrastructure. The proposed study and solution is of interest for most robotic laboratories when dealing with wireless connectivity problems. The authors claim that using this method they were able to improve the diagnosis of wireless connectivity issues as compared to manual methods.

C. Soft, Robust Robots for Children with Autism Spectrum Disorder

In this paper, Hong Tuan and Cabibihan [9] describe an experimental comparison between polyester resin and silicone rubber as casing materials for protecting robotic circuitry and servomechanism. The main motivation of the work is on enhancing physical robustness of social robots when used for therapeutic purposes, more specifically in interaction with children suffering autism spectrum disorder.

D. Adapting Low-Cost Platforms for Robotics Research

In this paper [10], Karimpanal et al. explain the design process of EvoBot, a low-cost, open source, general purpose platform to enable testing and validation of robotics algorithms. It has a differential base with two powered wheels and two casters. It includes Bluetooth, a Wi-Fi enabled camera and several sensors. The paper describes specially the design process and solutions of low-cost platforms for swarm robotics research, as well as the adaptation process of swarm robotics algorithms from simulation to real scenarios. The lessons learned when designing and adapting the robot are also discussed. Finally, the paper addresses how to adapt some common representative tasks for the platform, along with some potential problems and possible solutions.

E. Improvements and considerations related to human-robot interaction in the design of a new version of the robotic head Muecas

In this paper [11], Felipe Cid and Pedro Núñez describe some design improvements for a robotic head called “Muecas”. These improvements include both actuators and sensors aimed at providing the system with better communication capabilities for an enhanced human-robot interaction. The authors support their design decisions on some psychological theories based on emotional and communicational phenomena. The paper focuses on incremental design cycles for improving existent robotic platforms by incorporating new features and functions based on the lessons learned from the past.

F. Lessons from the Design and Testing of a Novel Spring Powered Passive Robot Joint

This article [12], written by Short et al, narrates the researchers’ journey towards the design, building and testing of a torsional spring joint. It focuses on the problems encountered during this process, as well as the lessons learned for the future.

One problem engineers are often dealing with is the short time schedule they have to make certain assumptions and estimations. This can often lead to troubles in the assembly and testing phase. As such, the spring joint prototype designed by the authors went twice through a cycle of assembly, testing, and redesign before the arriving at the final stage. During this process, the authors mention that they identified three problems and reported five learned lessons from their design experience.

G. Design, Simulation and Implementation of a 3-PUU Parallel Mechanism for a Macro/mini Manipulator

In [13], Zheng et al. present the design of a 3-PUU parallel mechanism which is used as a mini manipulator in a macro/mini manipulator configuration. The mechanism is suitable for applications requiring precision force control. The paper describes the shortcomings in the initial attempt to design the system and further discusses new methods and strategies adopted by the authors to overcome these deficiencies. The mechanism is a parallel kinematic mechanism for pure translation motion of the end effector platform. This is achieved through three prismatic actuators and three universal joints. The authors faced difficulties in achieving pure translation motion at the end effector and they successfully trace the source of the problems to be mathematical singularities and irregularities in the construction of the universal joints purchased off the shelf. The authors further demonstrate how they learn from the initial attempt failures and device a new parallelogram based configuration for the universal joint mechanism in order to reduce backlash.

H. Intelligence Level Performance Standards Research for Autonomous Vehicles

In this paper [14], written by Bostelman et al, the authors discuss standards development for performance of Autonomous Guided Vehicles (AGV) and optical measurement systems that are used to measure such vehicle performance. The paper discusses benchmarking standards for AGV and the issues faced with developing such a standard. The paper focuses on standards in four areas. Firstly, standards for vehicle navigation in order to measure uncertainties in navigation performance are detailed as currently this information isn't provided by the manufacturers. Secondly, standards to determine uncertainties in vehicle docking by measuring relative displacement from each of the points are described. Thirdly, standards for obstacle detection and avoidance are presented to study the reaction of AGV in different situations such as when a human is detected and interaction with machines that are operated manually. And finally, standards for 6DOF optical measurement of dynamic systems are discussed as these systems are needed for performing ground truth measurements of AGV performance. Experiments carried out for vehicle navigation, vehicle docking and optical measurement systems standards are also presented.

I. Gualzru's path to the Advertisement World

Presented by Fernández et al [15], in this paper the authors describes the genesis of Gualzru, a 1.60 m robot with an external cover built of resin and fiber glass, and a differential base with two powered wheels and two casters. It is commissioned by a large Spanish technological company to provide advertisements in open public spaces. The lessons learned during the three years of development from different points of view are explained including hardware, software, architectural decisions and team collaboration issues.

IV. CONCLUSION AND FUTURE WORK

With this first edition of the FinE-R (Failure in Real Robots) workshop we pretend to open a door for researchers to address the analysis and discussion of failures and methodologies when creating or designing robots. The workshop allows for sharing research experiences with scientists facing similar situations and problems. In this paper we also have provided a summary of the accepted contributions, in which the authors were asked to describe their path to success roadmap and to provide clear explanations of what they learnt while deploying their robotic projects that could be of interest for other researchers working in the same area.

Taking into account the quality of the accepted papers, the good response from the reviewers, program committee, and scientific community, as well as the importance that brings doing a deep analysis not only on the successful results but also on the path followed to reach them, as future work, we plan to continue organizing FinE-R in the context of IROS conferences. Our desire is that by keeping open this forum, the expertise of worldwide researchers gained along several years of working on robotic projects can be share with the scientific community. By doing so, not only better research projects can be conducted, but specially common or subtle failures can be avoided. In addition, we plan to open a special session or discussion panel where people participating on shared tasks or competitions like the DARPA Robotics Challenge[7], can explaining their experiences and problems encountered.

ACKNOWLEDGMENT

We want to thank to all the members of the program committee who helped during the review process and during the organization of the workshop. The full list of contributors and program committee members can be found at the workshop website[8].

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Skill-based Exception Handling and Error Recovery for Collaborative Industrial Robots

A. B. Beck, A. D. Schwartz, A. R. Fugl, M. Naumann, B. Kahl

Abstract— **Moving robots from their carefully designed and encapsulated work cells into the open, less structured human workspace for collaboration with workers requires robust error detection and recovery strategies. Foreseeing all possible uncertainties and unexpected events and to program in recovery actions at setup time is unfeasible. Online learning of nominal execution behaviour and automatic detection of anomalies using an Extended Markov Model, combined with interactively trained Bayesian networks for mapping anomalies to error causes and recovery actions, enables automatic recovery from previously experienced errors. A three-layered user-friendly model of errors—causes—responses and a simple GUI allows non-expert user to define new recovery activities and error causes when not yet handled anomalies occur.**

I. Motivation

Today's robot systems for industrial applications rely on a structured environment to avoid errors. Parts, fixtures, tools and stations have defined positions and the workspace is encapsulated to avoid intruders that could possibly endanger this defined environment. Expected exceptions from the nominal case that were either foreseen during the planning of the robot system, or occurred during the setup phase of the system are coped with by integrating additional sensors, adapting tool-, fixture and part geometries and adding additional branches to the robot program to cope with these deviations. Furthermore, as many robotic systems are complicated, any exceptions and breakdowns occurring after system setup often require external technicians or engineers to diagnose and solve problems.

Such strictly controlled and carefully designed work cells are only economically feasible if the designed robot system will run unobstructed for a long time. Small and mid-sized enterprises (SMEs) are often characterized by a much more agile production style and consequently rely on human workspaces. Moving robots out of their strictly controlled and carefully designed spaces into human workspaces, which are by nature unstructured environments with a high degree of uncertainty, requires significantly enhanced robustness towards unforeseen events and geometric or other uncertainties. (The additional need for safety measures to protect the human co-worker from injuries is out of scope of this work, see e.g. [22], [12] and many others.) A SME suitable robot system therefore needs semi automatic exception handling and error recovery capabilities that allow non-expert users to manage exceptions (internally and externally triggered) occurring in daily operation. We propose a novel skill-based exception handling and error recovery approach that allows non-robot expert users to operate a robotic system embedded in a human-centric workspace. We briefly introduce our execution model, detail the Extended Markov Chain based Situation Awareness, which forms the base for Exception Handling, and the Error Recovery module employing a Bayesian network and beta-binomial inference algorithm. The prosed system has been implemented in a pick & place and in an assembly work cell, which are finally presented.

II. Related Work

Research in exception handling is related to the area of error or fault recovery [17]. Error recovery has been defined as "the process by which the system returns to a state where production can restart after an abnormal and disruptive condition has occurred" [23]. For a robot coworker to effectively handle an exception, whether through informing the human worker or resolving the problem by itself, the types of faults that typically occur in the manufacturing robotic assembly cases needs to be understood. Fault taxonomies have been presented in other related fields, including mobile robots [7], computing [3], autonomous robots in RoboCup [21], workflow systems [16], service-oriented architecture [6], and web service [8]. Reports show that many errors in manufacturing systems, including CNC machines, are hardware related and that approximately 60% of all stoppages are due to tool breakdown [23]. However, there has been a lack of study on the likelihood of common errors and exceptions occurring during assembly tasks involving collaborative robots. One of the reasons can be that robot coworkers have not yet proven to be robust enough for industry application to be studied and generalized based on real assembly cases [14].

III. Skill-based execution model

At the base of the system is a Skill Execution Engine, which allows a more goal-oriented task description than strict motion based programming or planning. Without going into details of the skill-model [1], we assume skills to be independent, sensor-based motion or handling primitives that adapt themselves to position uncertainties and other deviations from an ideal state using build-in sensing and monitoring as well as (limited) internal error recovery. Robot tasks are constructed by chaining skills and control flow instructions, forming a state machine [2] based on SCXML[1]. While skills detect deviations from their expected performance and report these, the skill executor by itself does not provide any error recovery functionality. Features

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A. B. Beck and A. R. Fugl are with the Danish Technology Institute. E-mail: anbb@dti.dk and arf@dti.dk

N. Naumann is with the Fraunhofer Institute for Production Systems and Automation. E-mail: Martin.Naumann@ipa.fraunhofer.de

B. Kahl is with the Gesellschaft für Produktionssysteme GmbH Stuttgart. E-mail: bjoern.kahl@gps-stuttgart.de

[1] Apache Commons SCXML executor, http://commons.apache.org/proper/commons-scxml/.

of the skill executor that allow the implementation of error recovery functionality at higher layers are:

- The skill executor knows and publishes the current state of the system at any time. This allows an error recovery module to relate errors on the one hand to specific skill models and on the other hand to specific application steps and therefore to draw conclusions like "this is an error that is very typical for a pick operation" or "this is an error that occurred already in the past at this specific execution step of the application".
- The skill executor has an interface for an error recovery module to stop and later continue the execution of the skill based application program thereby allowing worker interaction to recover from errors detected by an error recovery module.
- The skill formalism used by the skill executor is built on the concept of reusable hierarchical skills that are easy to enhance or adapt. It is therefore easily possible to include additional mechanisms into an existing skill model to cope with errors that could be detected by the system but just have not been considered yet.

The Situation Assessment (SA) constantly monitors the overall situation (robot task execution) using data published by the skills executor as well as by additional sensors dedicated for situation assessment. Deviations flagged by the SA are further examined by the Exception Handling (EH), which devises a possible cause and corrective measure, potentially involving user interaction. The whole system of skill executer, situation assessment and exception handling is collectively referred to as "Exception Handling Framework" or "EHF".

IV. Situation Assessment

The role of Situation Assessment (SA) is to learn and monitor the (correct) skill execution and detect non-nominal conditions. Deviations from the learned, nominal behaviour are interpreted as Anomalies, which are passed on to the Exception Handler (section V). Our implementation of SA is based on prior work by [4] and [5], where SA was applied to mobile robotics. We implemented and expanded SA to learn skill based execution in a collaborative robotic system. To learn how to perform a skill correctly, SA captures the essence of the skill by learning the timing and sequence of events that make up the skill. Our approach is to generate one parameterized model that includes parameters in the space and time domain. SA learns the sequence of events within a skill execution by learning a set of parameters with a temporal component, recording the transition from one instantiation of the parameters to the next:

$$p(X) = p(X_1, X_2, \dots, X_n) \qquad (1)$$

where X, a *Situation Model*, denotes a set of parameters (a state), n denotes a discrete step in time, and p, a *Situation*, denotes the complete distribution of all the states within a skill. Each state X_i of X is parameterized:

$$X = [d_1, d_2, \dots, d_m] \qquad (2)$$

where d_i are data components such as sensor values or robot's internal state values.

A. Situation Model

Situation Assessment uses a *Situation Model* as a template description to fuse together the different data points for learning a Situation. The components of the Situation Model (d_i in (2)) are real number data, which can come from any source and have any meaning. In our experience, combining space and time is critical to the success of learning a skill. For instance, learning a skill using a 6D F/T sensor, the Situation Model s could be defined as in (3).

$$s_a = [primitive, F_x, F_y, F_z, T_x, T_y, T_z] \qquad (3)$$

The component $primitive$ of s_a is a data point that uniquely identifies the current primitive being executed in the skill. In this case, the unique primitive ID provides the understanding of time while the understanding of space is provided by the F/T data. By using the primitive ID we can learn a skill time invariantly. This means that SA will only learn the sequence of the events and is invariant towards the duration of the execution of specific primitives. We have found this feature particularly useful when the duration of the primitives or skills is stochastic. Should it be necessary to catch anomalies in relation to when events occur (e.g. too early or late), the primitive ID in (3) can be substituted with a time data point. Throughout our research, we have successfully applied SA to monitoring digital inputs, such as the state of one or more grippers. Through the rest of the paper, we will use the following Situation Model for implementation and testing:

$$s_b = [primitive, gripper_{open}, gripper_{closed}] \qquad (4)$$

where $gripper_{open}$ and $gripper_{closed}$ are binary outputs of reed switches of the gripper: $gripper_{open}$ is $true$ when the gripper is fully open and $gripper_{closed}$ is $true$ when the gripper is fully closed. Our assumption is that the gripper is grasping an object when both readings are $false$, indicating the gripper is neither fully open nor closed.

B. Data Processing and Clustering

The Situation Model serves as a template describing which sensors SA should fuse together into one single state. In general, all data points in the Situation Model have to be real numbers. This allows the computation of one single metric for each X_i in (1). We have so far used the Jaccard similarity coefficient as a method for clustering similar states. Through experimentation, we have found the algorithm to be useful despite its simplicity.

C. Dynamic Learning in Situation Assessment

SA can autonomously learn a skill without the user having to manually specify the states of a skill. We have implemented a spatiotemporal model that allows for online dynamic learning of states over time. For this purpose, we are currently using the Extensible Markov Model (EMM) as it is useful for online learning of sequences of states [10]. An example of a dynamically learned model using the EMM algorithm can be seen in Figure 1. In this example, a robot is picking up a nut from a table and placing it on a pipe in a single nonrecurring operation (therefore an open-ended chain). The EMM is also useful in learning looped tasks.

Figure 1. Example of learning a task. The upper left corner shows the temporal sequence of states the skill consists of. These states were learned online while the robot performed the task. A full video is available at https://www.youtube.com/watch?v=-CKbdQ3ocQo.

D. Anomaly detection

SA has two modes of operation: learning and detection during execution. In the learning mode, SA monitors the data points specified in the Situation Model and builds the Situation for the skill that is being learned. During execution of the same skill, SA loads the saved Situation and applies the same clustering process as during learning. However, should the clustering of the data result in a new state in (1), then SA will interpret that as an anomalous state has occurred and issue an Anomaly warning. Processing and handling the Anomaly is the task of the Exception Handler (EH) module.

V. Exception Handler

The task of EH is to receive an Anomaly from SA and provide a suggested solution that is most likely to solve the problem. For each robotic system, EH maintains a hierarchical four-layered Bayesian network with all exceptions and solutions relevant to that cell. The hierarchical structure allows EH to reason about the most suitable solution to a problem. EH provides the suggested solution to the user along with all other possible solutions. The user is free to select the suggested solution, any other solution or to create a new solution. The selection is stored in EH as a sample of user solution preference. Such samples are used in priming the network for inference with future anomalies. With the feedback of user samples, a closed preference-learning loop is formed to provide suggestions for solutions to future anomalies. In this section, we provide a detailed description of EH and begin with the role of the Exception Scenario ES in EH.

A. Exception Scenario

The Exception Scenario (ES) is designed as a four-layered model consisting of Anomaly, Error, Fault and Response, inspired by work in [18]. The hierarchy is a four-layered binary Bayesian network that facilitates inferring the most likely Response (solution) to an Anomaly (a deviation), an example is shown in Figure 2. At the lowest level of the network, Anomaly nodes model anomalies detected by SA. Each Anomaly node corresponds to a data component (d_i of (2)) in the Situation Model. Above Anomaly, the Error node models which kind of error the Anomaly is and if the Anomaly should even be considered an error. The Fault node models the root cause of the Anomaly and the Response node models the solution to the Fault. This model resembles the diagnosis model used by physicians when examining a patient: Based on symptoms (here: the detected error) an illness is inferred (here the fault) and a therapy decided (here the response). The intermediate step of a fault is necessary, since one and the same observed error (symptom) can have multiple causes. For example an unexpected gripper state can be due to a failed grasping operation, a missing object at the pickup position or a defective gripper itself.

B. Bayesian Network

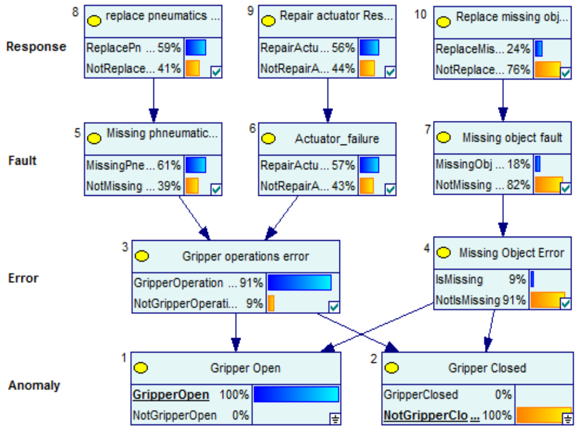

Figure. 2. Inference of cause and solution to *Gripper Open* anomaly. Both error nodes are dependent on both anomaly nodes, allowing the Bayesian network to further strengthen the belief about the cause of an anomaly. Simulated in GeNIe[1].

Figure 2 is an example of a Bayesian network with three Exception Scenarios for the two Anomaly nodes of the sensors $gripper_{open}$ and $gripper_{closed}$ in (4). Both Error nodes are dependent on both Anomaly nodes, allowing the Bayesian network to further strengthen the belief about the cause of an Anomaly (simulated in GeNIe[2]). The first two scenarios with nodes $s_1 = \{1,3,5,8\}$ and $s_2 = \{1,3,6,9\}$, offer two Responses to the Gripper Open Anomaly while the third scenario $s_3 = \{2,4,7,10\}$, offers a single Response to a Gripper Closed Anomaly. The numbers in curly braces indicate the node number in Figure 2. In this example we are modelling two faults {5,6} and Responses {8, 9} for the Gripper Open Anomaly. If a gripper is unexpectedly open (Gripper Open = true, Gripper Closed = false), we could interpret that as either a pneumatics failure (e.g. loss of air pressure) that can be solved by checking and replacing the air supply {5,8}, or an actuator failure (e.g. broken gripper) that can be solved by repairing the gripper {6,9}. In the reverse case of a closed gripper, we could interpret the failure as there was no object to grip and the solution is simply to replace the missing object. In Figure 2, the Faults {5,6} are modelled as belonging to the same Error, Gripper Operations Error {3}. This allows the network to learn user selections for a specific Fault, Response pair over other pairs belonging to the same Error node. The network is thereby able to encode knowledge specific to individual user environments.

[2] Figure 2 shows a screen capture of GeNIe, a Bayesian modelling environment developed by the Decision Systems Laboratory of the University of Pittsburgh. Available at http://genie.sis.pitt.edu

C. Inference

The process of inferring a Response to an Anomaly in the Bayesian network, is the inference process of the EH. This process is an implementation of Bayes' theorem:

$$posterior \propto prior \cdot likelihood \quad (5)$$

We have implemented Bayes' theorem in three steps:

- Calculate prior probabilities
- Introduce evidence to network
- Infer posterior probabilities

In the following, we describe each of these steps.

D. Inference

A prerequisite for performing inference is the calculation of prior probabilities. As described in section IV, a feature of the EHF is to learn the user-preferred solution of a given anomaly. When the user selects a specific Exception Scenario (i.e. an Error, a Cause and a Solution) to solve a problem, it is fed back to the database as a sample of the user selection, thus learning the preference of selecting this Exception Scenario for a specific Anomaly. The sample data is used to calculate the prior probability for each node of the network. We treat calculating the node's prior probability as an inference process that adds another layer of Bayesian inference as described in (5). We introduce the sample data from user selection of Exception Scenarios as the evidence to infer each node's posterior probability. Each node of the Bayesian network is a binary random variable modelling an event that either occurs or not. For instance, if the user selects the ES {1,3,5,8} in Fig. 2, then the user is confirming that the specific ES solved the problem (e.g. that a Gripper Open Anomaly did happen, it was caused by missing air pressure and the solution was to resupply the air). At the same time and equally important, the user is also confirming that alternative events {4,6} to ES {1,3,5,8} did not occur. Thus, with every selection of an ES, EH registers the confirmed nodes on all levels of the ES, as well as the rejected nodes. The process of selecting any node in the Bayesian network over time, can be viewed as a Bernoulli process following a binomial distribution as in (6).

$$X \sim \text{Binom}(n, p) \quad (6)$$

where X is the number of times a specific node has been selected. n is the number of samples drawn in the sequence. If this process is sampled sufficiently, a distribution reflecting the user selection can be inferred from the sample set. However, in many cases it is not possible to provide a sample set of sufficient size and inference will be subject to uncertainty. To model this uncertainty, we model the user selection for each node as a hyper-parameter p, thereby modelling the user selection as a random variable itself and creating a hierarchical Bayesian model for calculating the prior probability [11]. This approach uses the samples of user selection as a likelihood function providing evidence to the inference process. Given the binomial likelihood, we have chosen the Beta distribution as the prior distribution (7).

$$(p \mid \alpha, \beta) = Be(\alpha, \beta) \qquad (7)$$

In (7), the user selection is modelled as the hyperparameter p, drawing samples from the Beta distribution. α and β is respectively the number of samples confirming and rejecting the selection of the node. The Beta distribution is a conjugate distribution to the Binomial distribution, thereby offering analytical tractability of the Bayesian inference process. The conjugate property ensures that when updating the prior Beta distribution (7) with new evidence following the Binomial distribution, the resulting posterior distribution is also a Beta distribution (8).

$$(p \mid \alpha*, \beta*) = Be(\alpha*, \beta*) \quad (8)$$

$\alpha*$ and $\beta*$ is respectively the new number of selections and rejections for the specific node. Thus, obtaining the posterior distribution in (8) becomes simply a matter of adding new confirmations to the existing, and then calculating the mean (μ) and variance (var) (9,10).

$$\mu = \frac{\alpha}{\alpha+\beta} \quad (9)$$

$$var = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} \quad (10)$$

In Figure 3, examples of Beta distributions for different values of α and β are shown. Distribution 1: $Be(\alpha = 1, \beta = 1)$ is a uniform distribution offering an uninformative prior with a mean, $\mu = 0.5$ and a high variance (uncertainty) due to the low sample size. In this case, the posterior will largely be determined by the data. Distribution 4: $Be(\alpha = 30, \beta = 5)$ has $\mu = 0.86$ and a smaller variance, thus providing a comparably less uncertain estimate of the user selection preference, p. The sequence of graphs 1-4 in Figure 3, can be seen as an example of a continuous learning cycle, starting with no knowledge of user selection (a uniform

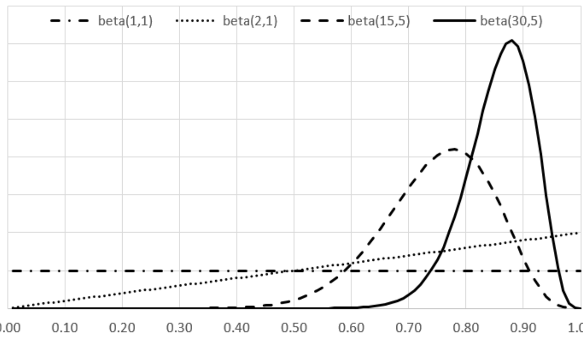

Figure 3. Four $Be(\alpha, \beta)$ distributions for different values of α, β. Note that $\alpha, \beta > 0$, thus $\alpha = \beta = 1$ is equal to no samples. 1: $Be(1,1)$, $\mu = 0.50$, $var = 0.083$. 2: $Be(2,1)$, $\mu = 0.67$, $var = 0.056$. 3: $Be(15,5)$, $\mu = 0.75$, $var = 0.0089$. 4: $Be(30,5)$, $\mu = 0.86$, $var = 0.0034$.

distribution with no samples) towards more informative distributions 2-4 as the sample size increases. When a new node is created with no samples available ($\alpha = \beta = 1$), the Beta distribution is uniform. However, to avoid the uninformative uniform distribution we propose to query the user to provide a subjective estimate of the selection (the mean) of this node along with a confidence level (the variance). Using the equations for the mean (9) and variance (10), suitable values for α and β can then be calculated.

E. Introducing evidence

The Bayesian network described in section V.B and Fig. 2 receives evidence in the form of Anomaly information gathered by SA. In the example shown in Figure 2, SA has detected that the gripper was unexpectedly fully open (thus providing evidence that Gripper Open = true, Gripper Closed = false. The evidence is in practice introduced to the network by clamping the two nodes to their respective values.

F. Posterior probabilities

After introducing evidence, posterior probabilities for all nodes are calculated. We have used the SMILE reasoning engine [9] for inference. The Response having the highest posterior probability is selected as the suggested solution. For each Response, the tree is descended towards the root Anomaly nodes, thus mapping out each possible path towards the root. The resulting list will have the most probable ES listed first with all other less likely alternative ES following in descending probability.

VI. User Interface for Error Recovery

While section V discussed the inner working of the actual mapping process, we focus on a more user-centric view in this section.

Whenever an anomaly is detected, the error layer classifies it into an error cause. If no cause is found the user is inquired and given the option to assign an existing cause, dismiss the anomaly as not indicating an error or to create a new cause (including a resolution, if known). Figure 4 shows the dialog box after successfully mapping an anomaly to an error and further to a recovery action. The user can accept

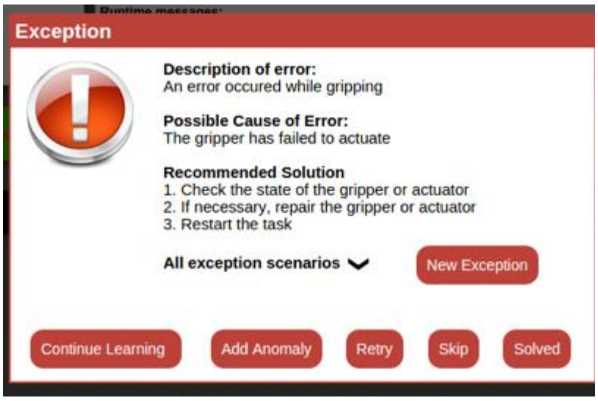

Figure 4 The system identified an error including a recovery action. In case of misclassification the user can add a new exception or dismiss the anomaly as not indication an error (button "Continue Learning").

this solution or add a new solution. Figure 5 shows the corresponding dialog box for adding a new triplet of error, error cause and recovery action. The dialog boxes shown in Fig. 4 and 5 are designed for use at system runtime and therefore as simplistic as possible. A more elaborated interface for managing the entire network of anomalies, errors, causes and recovery actions is also provided and targeted at specifically trained users that setup a new robot application.

VII. Experimental Evaluation

Within the scope of SMErobotics, this framework has been intensively evaluated using various experiments. A detailed example is the failure to grasp as described in the following section. We have tested the system's ability to learn the preference of selecting a solution by manually introducing the Gripper Open (GO) Anomaly, shown in Fig. 6, during the execution of a skill. In this test, we have tested the system's ability to learn the user preference of selecting the Repair Actuator (RA) Response over the Replace Pneumatics (RP) Response. For the purpose of the test, the system had initially no knowledge of user selections (samples), except for five samples confirming the choice of the RP Response as the user preferred solution to the GO

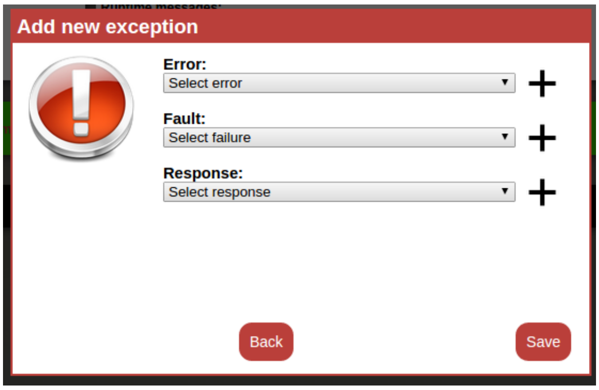

Figure 5 Adding a new error cause or fault to the system.

Anomaly. Hereafter, we introduced the GO Anomaly repeatedly, selecting the RA Response as the solution each time. This process was repeated until EH started to suggest the RA Response, thus demonstrating EHF's ability to learn the user preference of selecting the RA Response over the RP.

Test results are shown in Fig. 6. Initially, EH has five samples confirming the selection of the RP Response for the

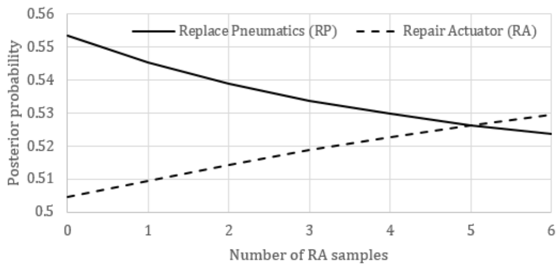

Figure 6. Posterior probabilities for solution nodes Replace Pneumatics (RP) and Repair Actuator (RA) to a Gripper Open Anomaly. The solid line represents the posterior probability of the RP and the dotted line represents posterior probability of RA. For one sample of RP, it takes EH two samples of RA to learn the user preference of selecting RA.

GO Anomaly. Thus, when the GO Anomaly is introduced, EH suggests RP as the most suitable Response to the GO Anomaly with probability ~ 0.553. However, the user ignores the EH suggested RP Response and instead selects RA. Thus, when the GO Anomaly is introduced again, EH now has six samples (five for RA and one for RP), computing the most likely Response to be RP with probability ~ 0.545, and so on. At RA sample 5, EH computes the probability for each Response being identical (~ 0.526). Again, the GO Anomaly is introduced and this time EH suggests the RA Response with posterior probability ~ 0.535. Thus, with five samples confirming RP, it took six samples of RA for EH to suggest RA.

VIII. Conclusion and Future Work

Through the test results in section VII, we showed that EH is able to learn the user preference of selecting a solution, even when it had learned a different preference earlier. As the user selects a specific solution to an Anomaly, the solution becomes more probable for future selection. This is normally helpful, but can be problematic if the user wishes the system to select a different solution, since learning a new preference can take several iterations, as the test results showed. This is especially true when the sample count for the prior solution is high. A possible future solution could be to introduce additional information in the Error Layer, e.g. condition the error cause not only on the counting of user selections, but also on the state of various system variables at time of the user selection.

The system is currently being integrated in further demonstrators in the context of the SMErobotics project and will see more in-depth testing and possibly enhancements in these demonstrators. Concept videos of these showing the SMErobotics vision of future industrial robotics are available at http://video.smerobotics.org; especially the D2 and D3 videos are relevant in the context of this work.

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Using Autonomous Robots to Diagnose Wireless Connectivity

Richard Wang, Manuela Veloso, and Srinivasan Seshan
Carnegie Mellon University

Due to the proliferation of wireless devices, many wireless users treat wireless connectivity as a black box. When wireless performance does not meet expectations, it can be a frustrating experience to try and resolve wireless issues. Wireless problems are more significant for mobile robots due to strenuous requirements for sustained wireless connectivity while moving [1]. Unfortunately, it can be difficult to understand the cause of wireless problems in real environments. First, wireless signals transmitted across the wireless medium are susceptible to attenuation, interference, and reflections from the surrounding environment and other wireless devices. Second, wireless connectivity depends on decentralized cooperation across heterogeneous devices. As autonomous robots are introduced in our environments, we believe they can be a perfect tool to capture detailed snapshots about our wireless environments to help diagnose wireless connectivity issues. In this paper, we show how these insights helped us to diagnose our robot's own motion-based wireless connectivity issues.

I. Introduction

Understanding wireless connectivity in real environments is hard. Much of the complexity stems from wireless transmissions occurring over an open, shared medium with a mixture of decentralized, heterogeneous devices [2]. Once devices begin to move, wireless problems become even more difficult to diagnose since wireless conditions around the device can change rapidly. The emergence of telepresence robots has shown that wireless devices in motion struggle to sustain uninterrupted wireless connectivity [1]. In this paper, we will show that autonomous robots can be a valuable tool for identifying the cause of poor wireless performance with direct observations of the wireless environment.

We focus on enterprise wireless networks composed of access points (APs) distributed throughout the environment to provide Internet access to devices at all locations. Today, motion-based wireless connectivity issues are difficult for users to resolve because:

1) wireless infrastructures are complex and vary over space and time
2) users have visibility and control over only their own device
3) wireless communication problems can require significant domain knowledge to deal with the range of hardware, drivers, and protocol layers

As a result, a natural reaction is to submit trouble tickets and wait some time for network administrators to come and resolve the problem. Even network administrators may struggle to resolve the wireless issues because: 1. they have limited time due to the large number of users to administrators (25,000 to 6 in our case), 2. the problem must be easy to replicate, and 3. network administrators control the infrastructure APs but have limited visibility of the wireless medium.

Autonomous robots as a wireless tool can augment diagnosis of wireless problems by:

1) capturing fine-grain wireless maps reflecting actual propagation of wireless signals
2) serving as a vehicle to subject wireless devices to repeatable motions

This is made possible due to their ability continuously localize with high accuracy and autonomously and precisely navigate without human assistance. Detailed wireless maps help to reveal how the wireless medium is being used in order to eliminate unlikely causes of poor connectivity. They would also allow wireless users to diagnose simple dead zone coverage issues and perhaps also empower them to create more meaningful trouble tickets. Since wireless problems with motion are often short-lived, the ability to reliably repeat motions is essential for understanding more complex motion-based wireless connectivity issues.

In this paper, we will first show that autonomous robots can be used to collect detailed wireless measurements. Next, we show fine-grain insights allow us to better understand how our wireless infrastructure uses the wireless medium. Finally, we show how we were able to diagnose our device's own motion-based wireless connectivity issues.

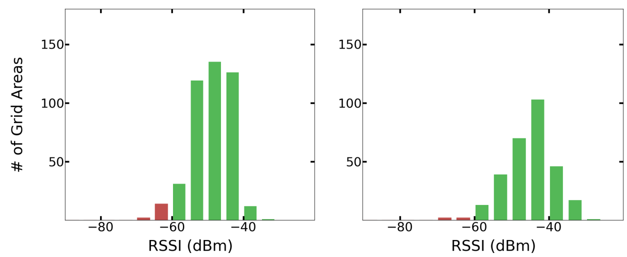
II. Insights about Surrounding Wireless Conditions

We now show the detailed insights that autonomous robots can capture without access to any sensitive wireless infrastructure APs. With these insights, we will be able to understand how the wireless medium is being utilize and see if possible infrastructure configuration issues may be causing our wireless connectivity issues.

A. AP Coverage

AP coverage ensures every location has at least one AP in range. Avoiding wireless dead zones is the responsibility of network administrators who manage the wireless infrastructure. They often try to place APs to provide a high minimum received signal strength indicator (RSSI) at every location. Our network administrators target a minimum RSSI of -60 dBm, which is much higher than -90 dBm that generally signifies no connectivity. The process of verifying coverage simply requires sampling RSSI at all locations in the environment. Unfortunately, there are no practical solutions that require little human effort and achieve fine-grain sampling of the environment. As a result, there are situations where trouble tickets result in the discovery of wireless dead zones in practice.

We can automate this search for wireless dead zones by deploying autonomous robots to measure coverage across the environment. We were able to cover four floors of our enterprise environment. Figure 1 shows a histogram of median RSSI of the best available AP after dividing the environment into 1m x 1m grid regions. We see that AP coverage across two floors is very strong with few regions falling below the -60 dBm target. If there had been wireless dead zones, they would have been apparent in these histograms. As a result, wireless issues for these floors are unlikely to be due to wireless dead zones.



(a) Floor 1 (b) Floor 2

Fig. 1: Coverage summary showing histograms of the best median RSSI for each floor. Network administrators typically aim for a minimum of -60 dBm coverage.

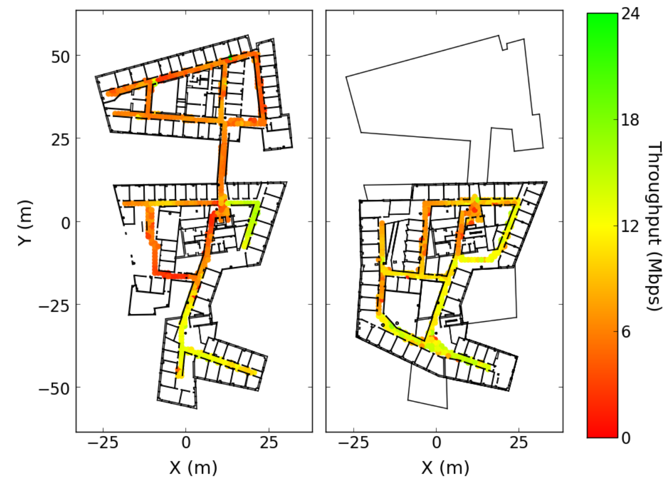
B. Throughput Samples

Coverage is an important pre-requisite for wireless connectivity but not necessarily reflective of the actual rate of data transmission. Unlike RSSI that are instantaneous measurements, throughput samples depend on state and co-ordination with other wireless devices. Throughput tends to vary more than RSSI since congestion and dropped packets affect the rate of data transmission. As a result, throughput maps are unliklye to be a predictable as the coverage maps.

Figure 2 shows throughput maps collect by the robot as it moved across the environment. These measurements show how wireless performance varies over space. We can see that our robot's own wireless connectivity problems are not isolated to small regions but spread across large regions of our building. This points to more systemic wireless issues that our robot is struggling with. If the robot was facing region-specific wireless issues due to excessive congestion, these types of throughput maps would have been helpful.

III. Diagnosing Motion-Based Wireless Connectivity

We have shown that our wireless infrastructure is well-configured and AP coverage is not an issue. Nevertheless, our throughput maps showed that motion-based wireless



(a) Floor 1 (b) Floor 2

Fig. 2: Median throughput across two floors.

connectivity issues still persist. From our own empirical observations, these wireless issues appear intermittent and seemingly random while moving around. When we bring the robot back to revisit locations where it lost connectivity, the connectivity issues would not occur again so these problems must arise with motion. Autonomous robots will help to better understand these motion issues since they can continuously collect of wireless performance measurements while also reliably executing controlled motions. With the autonomous robots, we will methodically diagnose the root cause by enabling humans to search for similar patterns that lead to these poor connectivity situations.

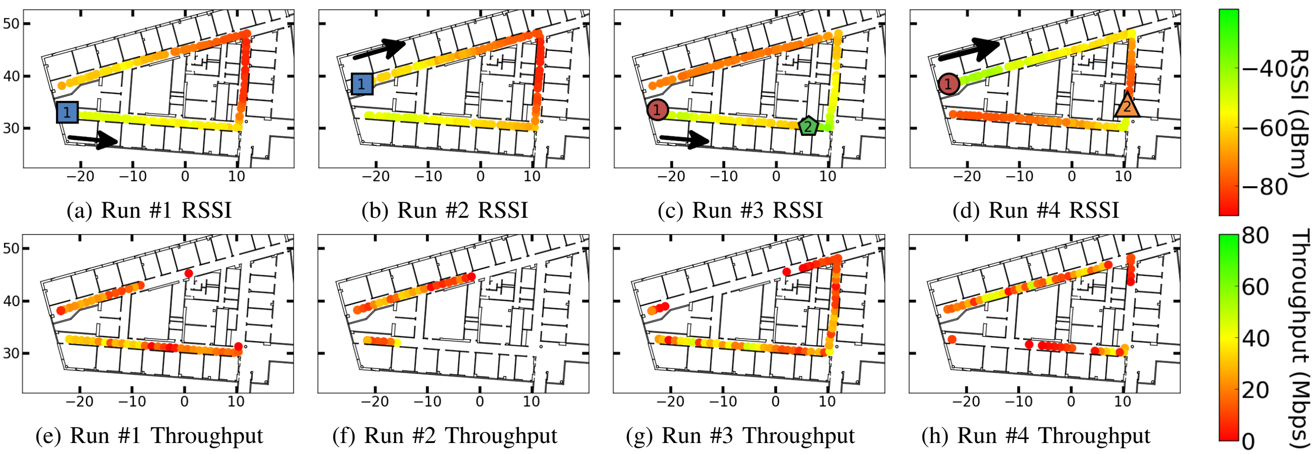
A. Repeated Motions

Many factors including location and speed of motion can cause variations in wireless performance so we subject the wireless device to nearly identical situations. An autonomous robot itself is perfectly suited for subjecting the device to repeated traverals over the same path with the exact same speeds and device orientations. Deploying an autonomous is much preferred over fixed contraptions that are cumbersome and require modifications to the environment [3].

The robot is instructed to follow a simple three-quarter loop path around three hallways in the environment where connectivity issues occur frequently, as shown in Figure 3. We even instruct the robot to move in both clockwise (Figure 3b and 3d) and counterclockwise (Figure 3a and 3c) directions. We intentionally select a path where the robot traverses each location at most once. With no overlapping measurements at any location, it will be much easier to analyze the wireless performance variations using wireless maps.

B. Analyzing Variations in Wireless Performance

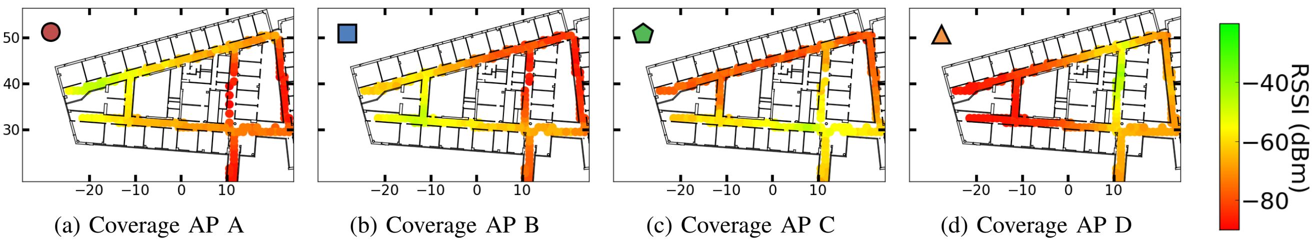
While being driven along the given path, the wireless device simultaneously captures RSSI, throughput, and current AP it is associated with. We present four noteworthy runs



(a) Run #1 RSSI (b) Run #2 RSSI (c) Run #3 RSSI (d) Run #4 RSSI

(e) Run #1 Throughput (f) Run #2 Throughput (g) Run #3 Throughput (h) Run #4 Throughput

Fig. 3: Simultaneous associated RSSI and throughput for 4 runs over the same locations. Runs 1 (3a) and 3 (3a) began in the bottom left corner with the robot moving counterclockwise while Runs 2 (3b) and 4 (3d) started in the top left and moved clockwise. Numbered labels reflect the first point of association with each AP while the shape and color reflect a unique AP whose corresponding coverage is shown in Figure 4.



(a) Coverage AP A (b) Coverage AP B (c) Coverage AP C (d) Coverage AP D

Fig. 4: Coverage for each AP corresponding to APs in Figure 3 identified with a unique shape and color.

in Figure 3 that shows RSSI (top), throughput (middle), and coverage for each AP (bottom). In the RSSI maps (top), the unique shapes reflect the location where the device first associated with the corresponding AP as identified by the color and shape. The numbered labels identify the order in which they were visited. We show AP coverage for each of these uniquely identified APs (bottom). Corresponding throughput while moving (middle) is also shown where large stretches of white space reflect absence of connectivity.

These four runs provide some noteworthy insights. First, RSSI changes gradually over several meters as a function of the device's distance from the AP. Notice that run #1 and #2 remained associated with the same AP for the duration of the traversal. Irrespective of the direction of motion, RSSI for these runs nearly perfectly matches corresponding AP coverage. For these runs, throughput resulted in lengthy stretches of no connectivity since the AP was out of range.

In run #3 and #4, the device switches to another AP in the middle of the path. This AP switch particularly benefits run #3 but not as much for run #4. The difference is that run #3 switches APs just as it is about to enter the strongest AP coverage region for the selected AP. In contrast, run #4 switches to an AP that is almost out of range.

We can see in Figure 4 that there is at least one AP with high RSSI along the entire path so AP coverage is strong. The motion-based challenges must stem from poor AP handoffs. The key challenges appear to be centered around timing disassociations before connectivity degrade significantly and then intelligently selecting the next AP to switch to. With the help of our autonomous robot, we are able to distinguish the effects of AP coverage, changing wireless conditions, and device motion to conclude that poor AP handoffs are the cause of our robot's wireless issues.

IV. Related Work

Past efforts to collect wireless measurements are unable to ensure fine-grain accuracy, densely cover spatially diverse areas, and provide timely updates. Unfortunately, it is difficult to predict the propagation of wireless signals in realistic, indoor environments so fine-grain wireless maps require measuring signals captured at each location. Measurement studies have been performed by having humans carefully traverse a building and mark their locations on a map [4], [5]. This is a tedious process that suffers from accuracy issues due to human errors that make it undesirable to repeat often so it will be difficult to ensure maps are up-to-date.

Dense deployments of static WiFi monitors can ensure timeliness but are limited by placement options for fixed location monitors and incur significant human effort and costs to deploy so typically they cannot achieve high spatial granularity. While some use dedicated sensor hardware [6], [7], [8], others reduce costs by adding WiFi dongles to available USB slots [9]. Distributed synchronization and hardware calibration enables creation of a single, unified view from measurements collected across all WiFi monitors. A global view can be used to infer aggregate performance metrics like number of active wireless clients, interference, loss rates, and utlization [6], [7], [10] and even infer missing packets [8]. These approaches are limited to the perspective of the wireless infrastructure and have difficulty accounting for unreceived wireless client transmissions. In this paper, we view the wireless network from the perspective of the wireless client by accounting for the client's movement and considering the client's intent of transmitting wireless data.

Other efforts attempt to crowd-source collection of wireless maps. These approaches end up sacrificing accuracy in order to easily collect measurements. GPS can be used to provide location estimates [11], [12] but it operates primarily in outdoor environment and suffers from poor location estimates of around 3 meters. FM signals [13] similarly suffer from the effects of indoor environments and cannot achieve accurate location estimates. Recent efforts to take advantage of powerful sensors including odometry, magnetometer, and WiFi found in cell phones have been shown to have an accuracy of 1.69 m [14], [15]. Roomba robots have also been used to collect wireless coverage maps by spinning in small grid areas [16], [17] but they cannot autonomously navigate to reduce human time and effort costs or execute complex motions like our robot can. Our work takes advantage of much more powerful sensors that can localize within 10 cm using a wheeled platform that can reproduce complex movements.

Previous efforts have proposed techniques to use predictions to reduce the duration of handoffs or inform applications to allow for prefetching data and reduce the impact of handoffs [18], [19]. Nearby access points have also been used to opportunistically help mitigate WiFi handoffs for moving vehicles when moving across multiple buildings [20]. Our work that helps to expose and reproduce fine-grain failures in AP handoffs for moving devices is orthogonal to these efforts as it provides a mechanism for robustly evaluating handoff solutions.

V. Conclusion

Diagnosing wireless connectivity issues can be difficult due to the many factors that potentially impact wireless performance. We showed how autonomous robots can help to methodically drill down to the root cause by capturing detailed wireless measurements that eliminate unlikely factors. We were able to identify AP handoffs as the reason for our own robot's motion-based wireless connectivity issue by analyzing variations in wireless performance while subjected to repeatable motions. This was a challenging wireless problem that arose from poor decisions dependent on accurate timing and it is unclear that we could have uncovered them without the accuracy and control of autonomous robots. Opportunities for future work include using these detailed wireless maps for better management of enterprise wireless networks, ensuring timely maps for wireless localization solutions, and automated diagnosis of wireless problems.

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Toward Soft, Robust Robots for Children with Autism Spectrum Disorder

Hong Tuan Teo and John-John Cabibihan

***Abstract*—A meltdown is one of the most challenging behaviors of children with Autism Spectrum Disorder (ASD), where a child could not calm down or too overwhelmed with a certain situation. Because social robots are becoming useful as a therapy tool between the therapist and a child with ASD, as robot designers, we want to anticipate that a robot could be thrown on the floor or to the therapist or caregiver. In addition, we want to investigate how to better protect the robot from being damaged. Typical robots are constructed in plastic material. In this paper, a sample of plastic material and a sample of silicone material were compared in a drop test experiment at the heights of 0.0254 m, 0.5 m, and 1 m. These heights simulate a possible situation where the robot can be dropped. Our result shows the differences in the impact between the silicone and the plastic samples. This work provides a baseline study as a step toward soft, robust robots for children with ASD.**

I. Introduction

Autism Spectrum Disorder (ASD) is characterized by a triad of impairments in social communication, social interaction and imaginative skills [1]. The Center for Disease Control in the USA estimates that 1 out 68 children are diagnosed with ASD. Some children with ASD could go into a meltdown because they could find themselves overwhelmed in a certain situation. Such situations could include loud noises, bright lights, strong smells, and many other situations.

Research efforts have been put into the field of social robotics in an attempt to use robots to assist humans in a diverse number of ways. Socially interactive robots are used to communicate, express and perceive emotions, maintain social relationships, interpret natural cues, and develop social competencies [2,3]. To ensure the suitability of the robot's design, research studies have been conducted to obtain requirements from the end-user group who are children with autism. Since these children have impaired communication, therapists, parents and teachers were asked to give their feedback on suitable design of robots [4]. Other efforts have also been made to compile a detailed set of design requirements that are not subjective, but can be generalized to most of the children's preferences [5,6]. Robots with overly mechanized appearances may also not derive the best results since too many exposed mechanical parts can cause the child to shift focus from the interaction itself [7,8].

H.T. Teo was with the Electrical and Computer Engineering Department, National University of Singapore, Republic of Singapore, 117576.

J.J. Cabibihan is with the Mechanical and Industrial Engineering Department, Qatar University, Doha, 2713, Qatar (e-mail: john.cabibihan@qu.edu.qa).

A robot is not meant to replace therapists but is meant to be used as a mediator to provoke interaction between the child and another person. The objective behind using robot is to increase their interactions through longer eye contacts, which are important to build the child's confidence level. This can be done through touching, playing and engaging in imitation games with the robot. By doing so, they are able to open up and allowing themselves to engage in discussion about the robot's activities.

Research studies have shown that using robots as therapeutic tool for autism often lead to increase in certain areas such as engagement, attention, spontaneous imitation and novel social behaviour such as joint attention [9-11]. Robots are nonthreatening and can be design in such a way that they are engaging and allowing productive interaction.

The current robots seen to date have internal components consisting of microcontrollers, mechanisms, sensors, and actuators. However, most of the robots are lacking the robustness in the design. Robustness refers to the ability to operate without failure when subjected to a variety of harsh handling conditions. In order for a robot to be robust, the robot must be able to absorb impact in situations such as dropping onto the concrete ground from high ground, thrown against the wall or knocked repeatedly by force.

The soft and robust features of a robot are especially important when children with ASD are in a meltdown situation. This will occur when their needs and wants are not met or when they are not able to adapt to the changes in the environment. If they lose control, the child may pick up a robot that is in sight and exert force on it. There is a possibility that the exterior structure housing the components will crack under impact with another structure. Furthermore, the robot may cease functioning because of damages in the internal components.

For a robot to be robust, the materials and the embedded technologies are important in ensuring that a robot can withstand harsh handling conditions. Materials that are able to cushion the impact upon landing are generally preferred. Such shock absorbing materials are commonly used by designers to protect products such as phones, hard disks and equipment. For example, a hard disk is incorporated with an accelerometer that will send a signal to immediately unload its head when it is under free fall. This prevents the hard disk's head from coming in contact with the platter, which can cause considerable damage to the device.

Most of the manufacturers prefer using plastic as the exterior structure for robots because it can be readily molded to shape. Rubber materials have generally excellent tensile strength, elongation, tear resistance, and resilience properties and are commonly used to function as a shock absorber, as vibration isolator or as dampers. Rubber has low modulus of elasticity, it is capable of sustaining a deformation and will return to its original dimension.

How well the robot reacts to the shock is dependent on the choice of material. In the next sections, we describe a series of drop test experiments at 0.0254 m, 0.5 m and 1 m heights. These heights simulate possible conditions that a robot might be subjected to.

II. Drop Test Experiment

A. Calibration of Accelerometer and Conversion of Units

An accelerometer was embedded in the internal structure of the test object. Acceleration is the rate of change of velocity over time. Dynamic responses can be inferred from the experiment to which the accelerometer is mounted. In order to convert the voltage output from accelerometer to acceleration in *G*, intermediate steps were needed. Firstly, the analog voltage reading from the output of the accelerometer was obtained under static acceleration when it was in the direction of Earth's gravity field (9.8 m/s^2). Secondly, this analog voltage value will be reduced when it is not in the direction of Earth's gravity field to obtain the difference with respect to 0 *G* point. Lastly, the value is divided by the sensitivity of the device to obtain the acceleration value in *G*. Calibration of the accelerometer and a conversion of unit were needed to convert the output analog reading to the correct corresponding *G* values. This conversion of values allowed better analysis of the results. As the output voltages reading from the tri-axis accelerometer are different from the ideal case, the axis had to be calibrated individually. Attention was be placed on the square root of the sum of the 3-axis as it represents the total acceleration acting on the device during the drop test experiment.

B. Experimental Samples

A proper cylindrical housing for the devices was first selected. The devices that were secured in the housing included a 9-volt battery to provide power supply to the Arduino board, accelerometer, and data logging device. Caution has been taken to ensure that there was enough space for the impact to take place. The side of the housing was designed not to hit the accelerometer during the impact to prevent erroneous reading.

Fig.1. Experimental samples, silicone (left), polyester (right).

With the structure selected, a polyester resin sample and a silicone rubber sample were prepared to identical size and shape for better comparison.

C. Procedures

The silicone rubber sample was subsequently brought to the 0.0254 m height and held in stationary position for a few seconds to allow the registration of 1 *G* value before dropping onto the concrete floor. Caution has to be taken to prevent exerting extra pressure to the experimental object to avoid erroneous readings. Any suspected pressure applied to the experimental object during the trials will not be used for analysis. Both samples were subjected to the same starting drop position with the cross sectional area of the sample parallel along to the axis of the concrete floor. The sample must land with the cross sectional parallel along the concrete floor during the impact and after the impact for accurate comparison. This experiment was conducted 8 times for the same height. The data from the drop test was then plotted out. This same procedure was repeated for other heights. After the experiment for the silicone rubber sample was completed, the same set of experiment procedure was applied to the polyester resin sample. An illustration of the experimental set-up is shown in Fig. 2.

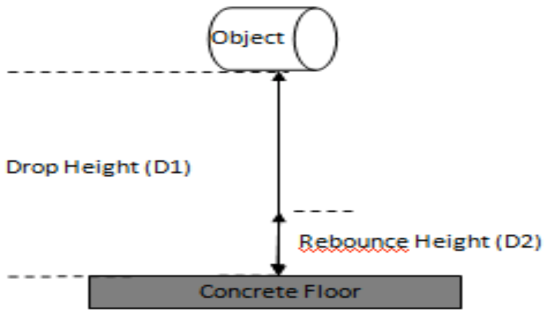

Fig. 2. Experimental set-up

III. Results

In this drop test experiment result, we focused on the acceleration peak and time interval between impact experienced by the material to the time that the material was at rest. Each figure shows the response graph at different heights.

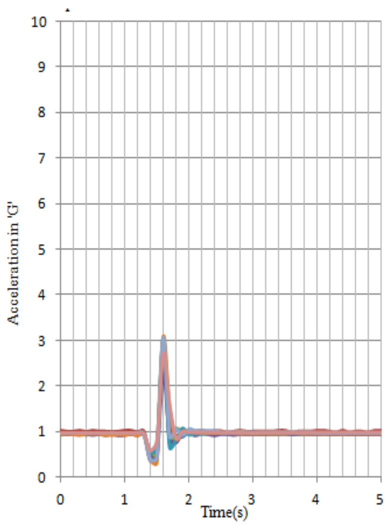

Fig. 3. Silicone Response at 0.0254m

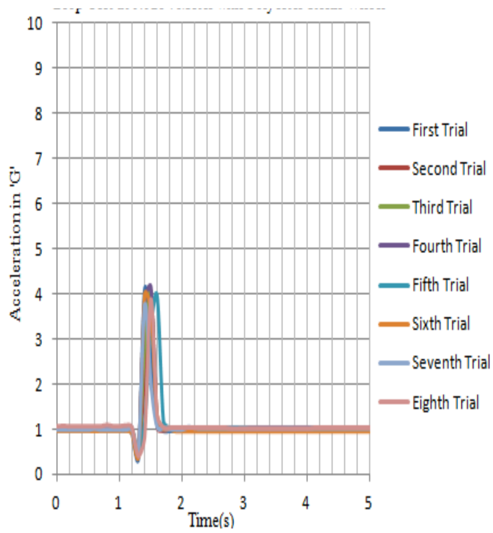

Fig. 4. Polyester Response at 0.0254m

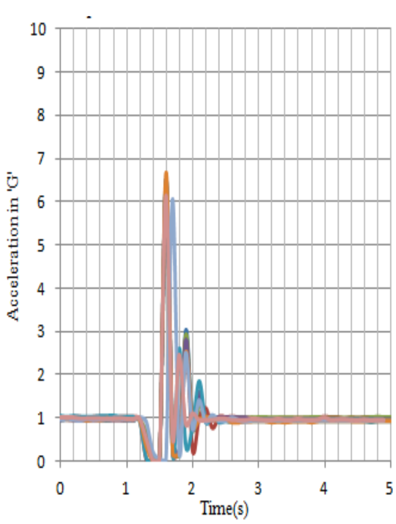

Fig. 5. Silicone Response at 0.5m

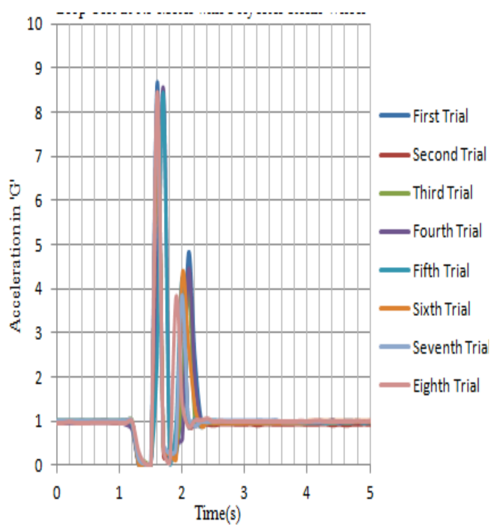

Fig. 6. Polyester Response at 0.5m

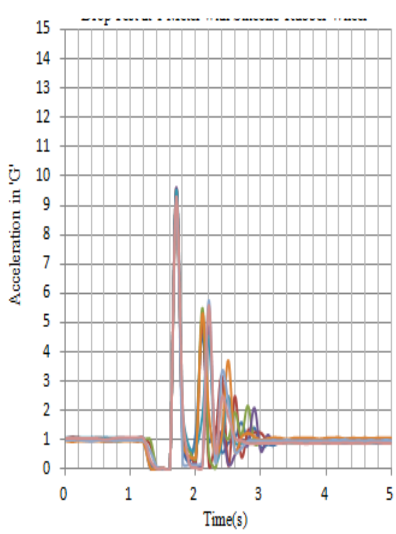

Fig. 7. Silicone Response at 1m

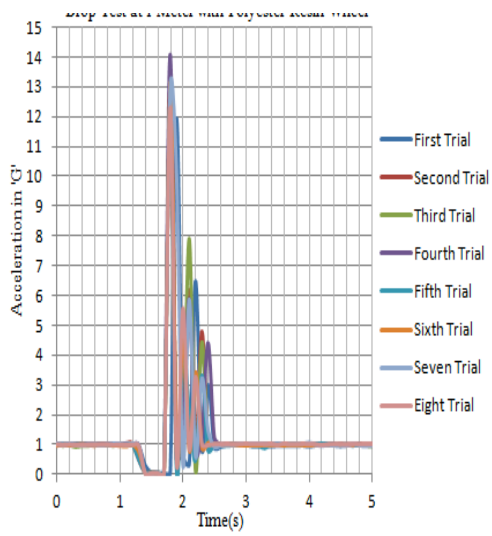

Fig. 8. Polyester Response at 1m

The settling time of a sample from the time of impact to the time the sample is at rest is shown in Table 1.

Height (m)	Material	Settling time response (sec)
0.0254	Silicone	0.4
0.0254	Polyester Resin	0.3
0.5	Silicone	0.9
0.5	Polyester Resin	0.8
1.0	Silicone	1.6
1.0	Polyester Resin	0.8

Table 1. Settling time response at different heights

From the experiment, it can be observed that the acceleration is much higher in polyester resin wheel than silicone rubber wheel especially during the first impact for the same drop height.

Acceleration is defined as the rate of change velocity over time. Since velocity is independent of mass during free fall period as it is under the influence of gravity (g = 9.8 m/s^2), the shorter the rate of change of time, the higher the acceleration. From Fig. 2, the downward velocity V_1 represents the velocity before the impact while V_2 represents the upward velocity after the impact. From Eqn. 1-3, the variables used were a_x (constant gravitational acceleration), x_f (final distance), x_i (initial distance), V_{xf} (final velocity) and V_{xi} (initial speed).

$$V_{xf}^2 = V_{xi}^2 + 2a_x(x_f - x_i) \quad (1)$$

$$V_1 = -\sqrt{2g(D_1)} \quad (2)$$

$$V_2 = \sqrt{2g(D_2)} \quad (3)$$

$$Acceleration = \frac{V_2 - V_1}{t_2 - t_1} \quad (4)$$

High acceleration especially for the first impact is harmful as it shows that the material is stiffer and does not respond well to the impact. It is noticeable that it took much longer time for the silicone rubber sample to settle down to stationary as compared to polyester resin sample. Longer time period shows the presence of elasticity in the material, which was required to absorb the shock within the material. Evidence of cracks was subsequently observed on the polyester resin wheels while the trials are being conducted at 1 m height. A comparison between the two experimental objects is shown in Fig. 9. Cracks are shown on the polyester resin sample.

Fig. 9. Results of drop test from 1 m height for silicone rubber (left) and polyester resin (right) samples. The polyester resin has noticeable cracks.

IV. Conclusion

Analysis of the experimental result shows that silicone rubber material displayed lower G value as compared to polyester resin, which was noticeable during the first impact. The subsequent number of damping is an indication of how well the material reacts to the impact. From the results, it can be concluded that rubber material took more time to react to the change of velocity during the impact as most of the impact would have been absorb and dissipated in the material.

Social robots are now being used as a tool for autism therapy and diagnosis [12]. Experiments have shown that children with autism prefer playing with interactive, robotic toys rather than passive toys [13,14]. They also direct more eye gaze and focus more attention towards robots [15]. Therapy for children with autism not only applies to their impairments but also to their growth needs, hence encompassing their educational needs as well. Robots are less intimidating than humans; they not only act as playmates for the child, but they can be used as small, colourful toys, ensuring that the child feels at ease during the interaction [5,14,16,17,18]. They can be programmed to adapt their behaviour in accordance to the specific needs of a child with whom it is interacting, hence customizing the therapy for a child [5,19]

The robustness of the robot is especially important when the child with ASD is in a meltdown situation. The consequences and damages due to the child's action during meltdown situation could not be predicted. The experimental result conducted from three different heights shows that silicone rubber material displayed lower G value noticeable on the first impact as compared to the response graph of the polyester resin. The rubber material took more time to react to the change of velocity during the impact as most of the shock would have been absorbed and dissipated in the material before changing the course of direction. This is different from the polyester material whereby it received most of the impact, which eventually lead to cracks. The outcome shows that rubber material is more robust and should be used to protect the hardware and software of the robot as it is capable of absorbing the impact better. Future work involves recreating and analyzing a scenario where an object is thrown to the wall.

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Adapting Low-Cost Platforms for Robotics Research

Karimpanal T.G., Chamambaz M., Li W.Z., Jeruzalski T., Gupta A., Wilhelm E.

***Abstract*— Validation of robotics theory on real-world hardware platforms is important to prove the practical feasibility of algorithms. This paper discusses some of the lessons learned while adapting the EvoBot, a low-cost robotics platform that we designed and prototyped, for research in diverse areas in robotics. The EvoBot platform was designed to be a low-cost, open source, general purpose robotics platform intended to enable testing and validation of algorithms from a wide variety of sub-fields of robotics. Throughout the paper, we outline and discuss some common failures, practical limitations and inconsistencies between theory and practice that one may encounter while adapting such low-cost platforms for robotics research. We demonstrate these aspects through four representative common robotics tasks- localization, real-time control, swarm consensus and path planning applications, performed using the EvoBots. We also propose some potential solutions to the encountered problems and try to generalize them.**

***Index Terms* — low cost, open-source, swarm robotics, lessons learned**

I. Introduction

The Motion, Energy and Control (MEC) Lab at the Singapore University of Technology and Design (SUTD) is engaged in an ambitious research project to create a swarm of autonomous intelligence-gathering robots for indoor environments. After reviewing commercially available low-cost robotics platforms, some of which are shown in Table I, the decision was taken to build a custom ground-based robot platform for performing swarming research, dubbed the 'EvoBot'. The primary trade-off is between platform flexibility and cost, where existing robots are intended to either be applied in specific research areas, and are hence equipped with limited and specific sensor and communication capabilities, or are more flexible with respect to sensor and firmware packages, but are also more expensive. In terms of software control development environments, well-established frameworks such as ROS [1] or the Robotics Toolbox [9] have extremely useful modular functions for performing baseline robotics tasks, but require substantial modification between applications and require specific operating systems and release versions.

With this in mind, the MEC Lab set out to develop the EvoBot platform with the following goals:

- Low cost: affordable for research groups requiring a large number of swarming robots (e.g. more than 50) with sufficient sensing and control features.
- Open source: The hardware, body/chassis design, application software and firmware for the EvoBots are fully open source in order to enable any group to replicate the platform with minimal effort. All the hardware and software files used for the design of the EvoBots is available here: https://github.com/SUTDMEC/EvoBot_Downloads.git
- Adaptable: The final platform is intended to be as general purpose as possible, with minimum changes needed to be made to the base firmware by users in order to scale to a wide variety of common research applications. Some representative applications are described in section IV. . . .

In the process of designing the EvoBots platform, a great deal of failure-based learning was involved, and this paper compiles and synthesizes this process in order for it to be useful for future robotics researchers who intend to develop their own platforms, or adapt commercially available platforms. Specific emphasis will be on challenges common to robotic platforms in general, and approaches used to avoid failure when attempting to solve them. The authors would like to point out that each robotics project presents a unique sets of problems, so we have attempted to only describe problems we think may be generalized.

II. Precedents and EvoBot Design

This section will discuss commonalities and differences between the EvoBot and other comparable low-cost robotics platforms, as well as provide insights into the lessons learned during the design process. In order to reduce the time between design cycles, the EvoBots were prototyped with a 3D printed body and developed across three major generations and several minor revisions. An exploded view of the EvoBot is shown in Figure 1.

Like the Khepera, Finch, Amigobot (table I) and most of the other platforms, locomotion on the EvoBot is achieved

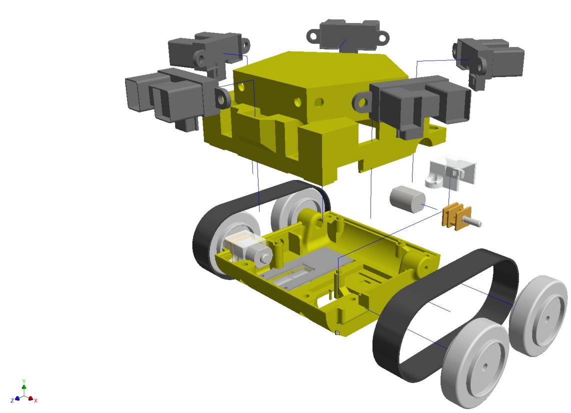

Fig. 1. The 3-D printed case has two slots at the bottom for the optical flow sensors, a housing for the left and right tread encoders, and 5 IR depth sensors. The encoders on the forward wheels and the optional ultrasonic sensors are not shown

TABLE I

PRECEDENTS FOR LOW-COST RESEARCH ROBOTICS PLATFORMS

Platform	Est. Cost (USD)	Commercial	Scholar Hits	Schematics	Code
Khepera [19]	2200	Yes	>1000	No	Yes
Kilobot [22]	100+	Yes	82	No	Yes
e-Puck [18]	340+	Yes	>1000	Yes	Yes
Jasmine [4]	150+	No	>1000	Yes	Yes
Formica [11]	50	No	10	Yes	Yes
Wolfbot [6]	550+	No	4	Yes	Yes
Colias [3]	50+	No	>1000	No	No
Finch [17]	100	Yes	73	No	Yes
Amigobot [2]	2500	Yes	170	No	Yes
EvoBot	300	Yes	0	Yes	Yes

using a differential drive system, with motors on either side of its chassis. Although this system introduces kinematic constraints by restricting sideways motion, the associated simplicity in manufacturing and assembly, and in the mathematical model for use in control applications are significant advantages. The wheels are coupled to the motors through a gearbox with a gear reduction ratio of 1:100. After reduction, the final speed of the robot can be varied from -180 to 180 mm/s, so that both forward and backward motions are possible.

The speed of each motor is controlled by a pulse width modulated voltage signal. In order to ensure predictable motion, an internal PI controller is implemented by taking feedback from encoders that track the wheel movement. The controller parameters may need to be hand-tuned to compensate for minor mechanical differences between the two sides of the robot, arising from imperfect fabrication and assembly.

For obstacle detection and mapping applications, 5 infra-red (IR) sensors were placed on the sides of a regular pentagon to ensure maximum coverage, with one IR sensor facing the forward direction. Similar arrangement of range sensors is found in platforms such as Colias and e-puck (table I). Despite this arrangement, there exist blind spots between adjacent sensors, which could lead to obstacles not being detected in certain orientations of the robot relative to an obstacle. The use of ultrasonic sensors instead of IRs, could reduce the probability of occurrence of blind spots due to their larger range and coverage, but they are also more expensive. It is thus advisable to choose sensors appropriately and to thoroughly test their performance and limitations before a final decision on the physical design and sensor placements is made.

Another feature present in the EvoBots common to other platforms is the use an inertial motion unit (IMU). The 6DOF IMU gives information regarding the acceleration of the robot in the x, y and z directions, along with roll, pitch and yaw (heading) information. Although in theory, the position of the robot can be inferred using the IMU data, in practice, these sensors are very noisy, and the errors in the position estimates from these sensors are unacceptably high even after using methods such as the Kalman filter [15]. Although obtaining the position estimates from the IMU is not recommended in general, good estimates can be obtained with units that are capable of a much higher resolution and data rate. Such units however, come at an expense and thus may not be the ideal choice for a low-cost platform.

A. Sensing Features

While the sensors mentioned earlier in this section focused on features shared with other platforms, there are some sensing, control and communication features specific to the EvoBots.

In almost all robotics applications, errors in the robot's position estimates may gradually accumulate (e.g. for ground robots, skidding or slippage of the wheels on the ground surface confound the wheel encoders). In the first two generations of the EvoBots, this error in the wheel encoders caused substantial challenges for localization. In order to tackle this problem, optical flow sensors were placed on the underside of the EvoBot. They detect a change in the position of the robot by sensing the relative motion of the robot body with respect to the ground surface. This ensures that the localization can be performed more reliably even in the case of slippage. As shown in Figure 1, there are two such sensors placed side by side at a specific distance apart. This arrangement allows inference of heading information of the robot along with information of the distance traveled. Although the optical flow sensors perform well in a given environment, they need to be calibrated extensively through empirical means. In addition, it was found that the calibration procedure had to be repeated each time a new surface is encountered, as the associated parameters are likely to change from surface to surface.

As described above, the wheel encoders, optical flow as well as the IMU sensors can all be used to estimate the robot's position and heading. Each of these becomes relevant in certain specific situations. For example, when the robot has been lifted off the ground, the IMU provides the most reliable estimate of orientation; when the robot is on the ground and there is slippage, the optical flow estimates are the most reliable; and when there is no slippage, the position estimates from the encoders are reliable. Some details on the use of multiple sensors for localization are mentioned in section IV-A.

In their current configuration, the EvoBots also include the AI-ball, a miniature wifi-enabled video camera with comprehensive driver support and a low cost point to capture video and image data [25]. The camera unit is independent of the rest of the hardware and thus can be removed without any inconvenience if it is not needed.

B. Control and Communication Features

There are a wide variety of microcontrollers which are presently available on the market. The chipset used on the EvoBot is the Cortex M0 processor, which has a number of favorable characteristics such as low power, high performance and at the same time, is cost efficient, with a large number of available I/O (input/output) pins. One of the primary advantages of this processor is that it is compatible with the mbed platform (https://developer.mbed.org/), which is a convenient, online software development platform for ARM Cortex-M microcontrollers. The mbed development platform has built-in libraries for the drivers, for the motor controller, Bluetooth module and the other sensors.

Like the e-puck, the EvoBots have Bluetooth communication capability. After experimenting with various peer-to-peer and mesh architectures, it was determined that in order to maintain flexibility with respect to a large variety of potential target applications, having the EvoBots communicate to a central server via standard Bluetooth in a star network topology using the low-cost HC-06 Bluetooth module was the best solution. Sensor data from the various sensors gathered during motion is transmitted to the central server every $70ms$. The camera module operates in parallel and uses Wi-Fi 802.11b to transfer the video feed to the central server. The Bluetooth star network is also used to issue control commands to the robots.

In addition, having a star network topology with a central server indirectly allows additional flexibility in terms of programming languages. Only a Bluetooth link is required, and all the computation can be done on the central server. For example, the EvoBot can be controlled using several programming languages, including (but not limited to) C, $python$ and $MATLAB$. The Bluetooth link also opens up the possibility of developing smartphone mobile applications for it. Table II summarizes all the sensors used in the EvoBot.

TABLE II
THE FINAL SENSING CAPABILITIES OF THE 3RD GENERATION EVOBOT PLATFORM

Signal	Sensor	Frequency	Full Range Accuracy
acceleration	MPU6050	1000 Hz	+/- 0.1%
Temperature	MPU6050	max 40 Hz	+/-1 °C from -40 to 85 °C
x/y pixels	ADNS5090	1000 Hz	+/- 5mm/m
Encoders	GP2S60	400 Hz	+/- 5mm/m
Battery current	ACS712	33 Hz	+/- 1.5 % @ 25C
Proximity	GP2Y0A02YK0F	25 Hz	+/- 1mm
Camera	AI-ball	30fps	VGA 640x480

III. General Problems

The EvoBot platform was designed to be useful for a wide range of research problems, and to enable researchers working in theoretical robotics to easily shift their algorithms from simulation to hardware. Moving from virtual to real platforms introduces a set of additional issues which must be considered. Some of these, which were encountered while developing applications for the EvoBots, are discussed in this section.

A. Sensing

While it may be considered acceptable to use ideal sensor models in simulation, in real-world robotics applications, and especially in the case of low-cost platforms, sensing information about the environment can be done only with a certain degree of range and accuracy. It is thus important to be judicious in choosing the location of the sensors. For the case of range sensors for obstacle detection, blind spots must be avoided as much as possible to prevent unexpected behaviours. Also, the upper and lower limits of the sensor range must be considered. As in the case of the EvoBots or other low-cost platforms, the sensor range may be quite limited and prone to noise, and blind spots exist despite careful sensor placement. In case of occurrence of blind spots, it may be worth encoding default behaviours into the robot such as conditional wall following or automatic steering away from detected obstacles.

B. Calibration

The behaviour of sensors are typically considered to be same for different environments during simulation. In practice, most sensors need some form of calibration. In addition, the calibration parameters for certain sensors may depend on the environment in which they operate. For example, the calibration parameters for the optical flow sensors in the EvoBots vary based on the surface on which they operate. In addition, the parameters are very sensitive to small variations in ground clearance which can be caused by variations in the robot body due to imperfect 3D printing or during assembly. It is often the case that parameters will have to be set and reset from time to time. This can considerably add to development time and effort. Automating the calibration process should be done whenever possible. If automation is not possible, one way to mitigate this issue is to have the software package include user commands that can change calibration parameters on the fly. This was the solution adopted for the EvoBots in order to calibrate the encoders and optical flow sensors.

C. Timing

In simulation, the robot's update loop and solvers can have either fixed or variable time steps, but it is most likely to be variable in practice. Thus, keeping track of time is critical, especially for real-time applications. For example, in the EvoBots, the performance of the localization algorithm (section IV-A) significantly depreciates if the time step is considered fixed.

D. Communication

When a large amount of sensor data and instructions needs to be exchanged between platforms or between a platform and a central machine, maintaining the integrity of the communicated data is critical. When the exchanged information is delayed or lost either partially or completely during information exchange, it could lead to a series of unwanted situations such as improper formatting of data, lack of synchronization, incorrect data etc., These aspects are seldom accounted for in simulation. In the EvoBots, the issue of lack of data integrity was tackled by performing cyclic redundancy checks (CRC) [21] as part of the communication routine. It is ideal to perform bit-wise checks as well, but this has not been done in the case of the EvoBots.

The issues listed in this section apply to almost all robotics applications in general. The following section discusses some of the applications and the associated issues encountered during their implementation using the EvoBots.

IV. Applications

This section discusses application-specific issues in diverse sub-fields of robotics such as real-time control, swarm and artificial intelligence applications. These applications were selected because they are commonly implemented tasks from a wide variety of sub-fields in robotics.

A. *Localization*

Ground robots typically need to have an estimate of position and heading. The EvoBot platform, as well as many other robots, are designed to be used in an indoor environment, and therefore it is not possible to use GPS without modifying the environment in question; also, positioning information provided by GPS has the accuracy in the order of a 10^1 meters which is not suitable for small ground robots. For this reason, the set of on-board sensors are used to estimate the robot's states of position and heading. The on-board sensors however, are typically associated with some noise and retrieving positioning information from them leads to erroneous results. For instance, integrating acceleration data to get the velocity and position does not provide accurate state estimation and leads to huge offsets from the true value due to the associated noise. To overcome this issue, state estimation is performed using a method based on the Extended Kalman Filter [15].

We used the information provided by the wheel encoders, optical flow sensors and the heading provided by IMU's gyroscope to estimate the position and heading. The sensor information is combined with the mathematical model of the robot to estimate the position and heading of the robot. Figure 2 presents the result of an experiment where two robots follow a trajectory (red line) and the data from the sensors are used in the extended Kalman filter to estimate its position and heading. In the next two paragraphs we explain two problems we faced while implementing the designed Kalman filter and we describe the corresponding solutions used in our platform.

Timing is one of the most important factors for localization and control tasks. The delay in communication between the robot and central computer where the Kalman filter is running, causes some variation in the time intervals within which each sensor data package is received. For example, the time intervals can vary between 50 to 100 ms Therefore, as mentioned in section III, the sampling time in the extended Kalman filter cannot be fixed a-priori. The state estimation procedure highly depends on the corresponding sampling time and using a fixed sampling time leads to a large error

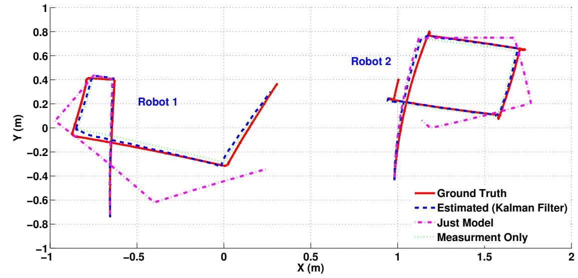

Fig. 2. The Kalman Filtering process improves the state estimate beyond what the model and the measurements are capable of on their own.

in the estimated state.One solution to this problem is to label each sensor data package with time, compute the sampling time on the central computer and use the computed real-time sampling time in the extended Kalman filter formulation. With these factors in mind, labeling the sensor data package with time seems to be an efficient solution to deal with variable sampling time.

A common problem associated with estimating the state using the velocity sensors is "slippage". In cases where a robot slips on the floor, the wheel encoders reflect an erroneous result. In the worst case, when the robot is stuck, the encoders keep providing ticks as if the robot is moving, which leads to a significant error in the estimated position. To solve this, we utilized the information from the optical flow sensors and designed an adaptive Kalman filter. The velocities reflected by the encoders and optical flow sensors are compared and in case there is a significant difference between them, the occurrence of slippage is inferred. Then, the noise covariance matrix in the extended Kalman filter is changed so that the filter relies more on the velocity provided by the optical flow sensor. Thus, we infer that although having multiple sensors sensing the same quantity may seem redundant, each of them, or a combination of them may be useful in different contexts.

B. *Application in Real-time Control*

In a perfect scenario where there is no disturbance and model mismatch, it is possible to use some feed-forward control to drive the robot on a desired trajectory. However, in the real world, a number of issues such as model mismatch, disturbance and error in the internal state deviates the robot from its desired path. Therefore, feedback control is vital to achieve an accurate tracking behavior. In general, the navigation problem can be devised into three categories: tracking a reference trajectory, following a reference path and point stabilization. The difference between trajectory tracking and path following is that in the former, the trajectory is defined over time while in the latter, there is no timing law assigned to it. In this section, we focus on designing a trajectory tracking controller.

The kinematic model of our platform is given by:

$$\dot{x_c} = \left(\frac{v_1 + v_2}{2}\right) \cos\theta_c$$
$$\dot{y_c} = \left(\frac{v_1 + v_2}{2}\right) \sin\theta_c$$
$$\dot{\theta}_c = \frac{1}{l}(v_1 - v_2) \quad (1)$$

where v_1 and v_2 are velocities of right and left wheels, θ_c is the heading (counter clockwise) and l is the distance between two wheels. As stated earlier, one of the reasons for adopting a differential drive configuration for the EvoBot is the simplicity of the kinematic model (1). Hereafter, we use two postures, namely, the "reference posture" $p_r = (x_r, y_r, \theta_r)'$ and the "current posture" $p_c = (x_c, y_c, \theta_c)'$. The error posture is defined as the difference between reference posture and current posture in a rotated coordinate where (x_c, y_c) is the origin and the new X axis is the direction of θ_c.

$$p_e = \begin{pmatrix} x_e \\ y_e \\ \theta_e \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{pmatrix} (p_r - p_c). \quad (2)$$

The goal in tracking control is to reduce error to zero as fast as possible considering physical constraints such as maximum velocity and acceleration of the physical system. The input to the system is the reference posture p_r and reference velocities $(v_r, w_r)'$ while the output is the current posture p_r. A controller is designed using Lyapunov theory [16] to converge the error posture to zero. It is not difficult to verify that by choosing

$$\begin{cases} v_1 = v_r \cos\theta_e + k_x x_e + \frac{l}{2}\left(w_r + v_r(k_y y_e + k_\theta \sin\theta_e)\right) \\ v_2 = v_r \cos\theta_e + k_x x_e - \frac{l}{2}\left(w_r + v_r(k_y y_e + k_\theta \sin\theta_e)\right) \end{cases} \quad (3)$$

the resulting closed-loop system is asymptotically stable for any combination of parameters $k_x > 0$, $k_y > 0$ and $k_\theta > 0$.[1] The tuning parameters highly affect the performance of the closed loop system in terms of convergence time and the level of control input applied to the system. Hence, we chose parameters k_x, k_y and k_θ based on the physical constraints of our platform e.g. maximum velocity and acceleration. Extensive simulation is performed to verify the controller (3). Figure 3 shows some *experimental results* where the robot follows a reference trajectory (blue curve). The reference trajectory is a circle of radius $1m$. The initial posture is selected to be $(0, 0, 0)'$. Errors $x_r - x_c$, $y_r - y_c$, and $\theta_r - \theta_c$ are shown in Figure 4. We remark that reference linear and angular velocities v_r and w_r are difficult to obtain for arbitrary trajectories. We solved this problem using some numerical methods where the point-wise linear and angular velocities are computed numerically.

[1]Choosing $V = \frac{1}{2}(x_e^2 + y_e^2) + (1 - \cos\theta_e)$ and taking its derivative confirms that $\dot{V} \leq 0$. Hence, V is indeed a Lyapunov function for the system (1).

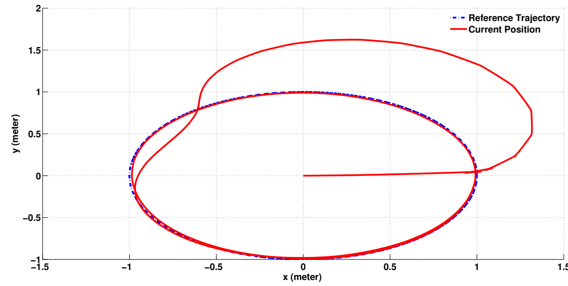

Fig. 3. The trajectory of the robot

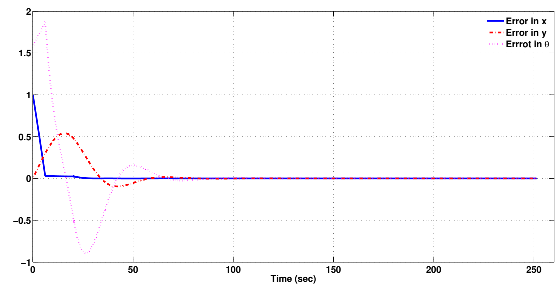

Fig. 4. The errors in x, y and θ

One of the important factors in implementing the real time controller is time synchronization. The controller needs to keep track of time in order to generate the correct reference point. This issue is critical especially when a number of robots need to be controlled. In this scenario, an independent counter can be assigned to each robot to keep track of its time and generate the correct reference point at each time step.

C. Application in Swarm Robotics

The overarching application of the EvoBots platform is to enable low-cost swarm robotics research. The study of emergent collective behaviour arising from interactions between a large number of agents and their environment is an area which is gaining increasing importance recently. The robots used for these purposes are usually simple and large in number, with communication capabilities built into them. Although it is ideal to have peer-to-peer communication between the agents, the same effect can be simulated through a star-shaped network, where all the agents share information with a central machine.

A typical swarm robotics application is to have the swarm arrive at a consensus about some common quantity, and to use this as a basis to collectively make decisions about the next actions of each member [5]. Figure 5 shows the configuration of a set of 6 robots at different times. The heading/orientation of each robot depends on those of the other robots and is governed by the update equation:

$$\theta_i \leftarrow \theta_i + K(\theta_m - \theta_i) \quad (4)$$

where

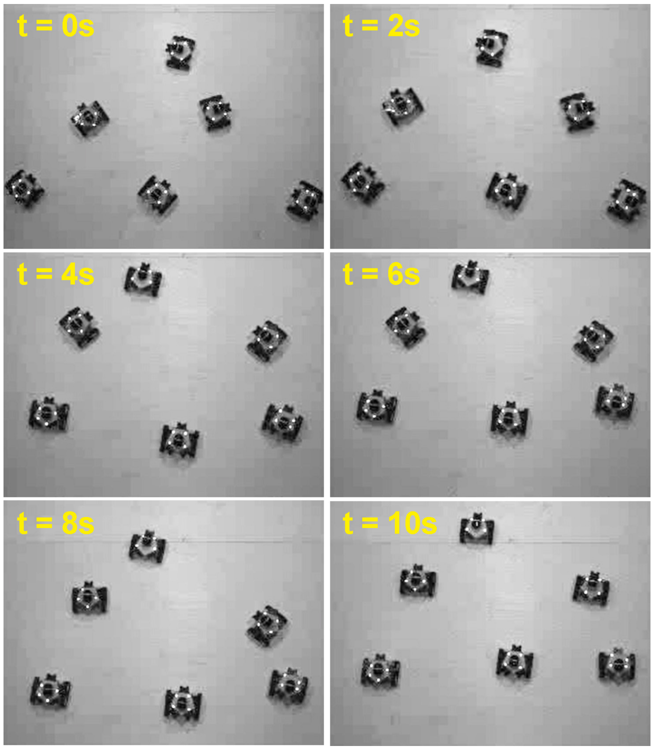

Fig. 5. Overhead view of the robots at different times during the heading consensus. The robots are initially unaligned, but arrive at a consensus on heading at t=10s

$$\theta_m = \sum \theta_i / N \tag{5}$$

Here, θ_i is the heading of an individual agent, K is a constant and θ_m is the mean heading of all N agents. These updates are performed on each agent of the swarm till the heading converges to the same value.

As seen from Figure 5, the robots eventually orient themselves in a direction that was determined using the consensus algorithm.

Swarm algorithms rely on the current information regarding other members. So, delays in communication can cause swarming algorithms to diverge instead of converging. As mentioned in section III, performing routines to maintain the integrity of the exchanged data is critical. The communication rate should ideally be independent of the number of agents involved. Usually, in communication systems, it is common practice to make use of communication data buffers. For swarm applications, one should ensure the latest data is picked out either by matching similarity in time-stamps or by refreshing the buffer before each agent is queried.

D. Application in Artificial Intelligence

One of the long-term goals of robotics is to develop systems that are capable of adapting to unknown and unstructured environments autonomously. The general set of tools

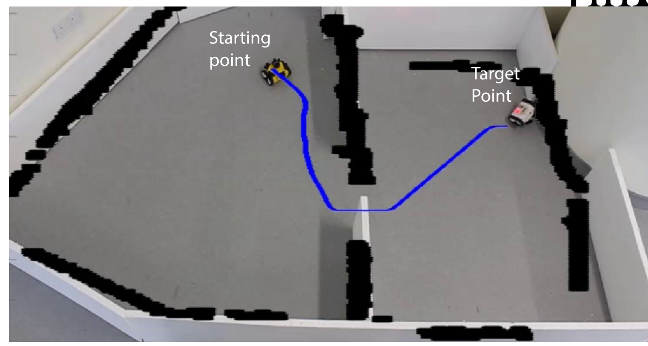

Fig. 6. Planned path of the robot shown in blue

designed to enable this objective falls under the fields of machine learning and artificial intelligence (AI). This includes approaches such as neural networks [14], support vector machines [10], evolutionary robotics [20], reinforcement learning [23], probabilistic methods [24], etc., which are used for a range of tasks such as object recognition, clustering, path planning, optimal control, localization and mapping etc. Although most algorithms can be tested out in a simulated environment, the uncertainties and nuances associated with a real environment limit the utility of simulated solutions, especially in fields such as evolutionary robotics [7], [8], [12]. A more thorough validation necessitates implementation of these algorithms on real-world physical systems.

To illustrate some of the primary issues and requirements of a platform for use in AI, a path planning task is demonstrated using the standard A-star algorithm [13]. The scenario involves planning a path from the starting position of a robot to a target position using a previously constructed infra-red sensor based map of the environment as shown in Figure 6. Most of the arena shown in Figure 6 has been mapped; the mapped areas are shown as black patches along the boundaries of the arena. The planned path (shown in blue) is generated by the A-star algorithm, using cost and heuristic functions. The heuristic function is proportional to the euclidean distance from the target position. Some of the important issues while implementing this algorithm for path planning and for AI applications in general, are listed below:

Computing Resources: The A-star algorithm could have also been implemented locally on the robots. However, this would have implied storing a copy of the IR map and performing the A-star algorithm locally using this map. This may not have been feasible due to the limited on-board memory and computational complexity of the algorithm.

Also, for path planning, the map of the environment gets larger as the space explored gets larger. Accordingly, the A-star path planning could potentially become more computationally intensive. So setting a resolution parameter (or deciding to have one) is recommended before starting the mapping.

In general, sufficient computing resources will be needed to carry out AI algorithms. Having a thin client system that offloads the computational effort to a central server helps deal with the high computational costs imposed due to high dimensionality in certain problems.

Dealing with the real world: Readings from the robot's sensors involve an inherent component of noise, even after they have been calibrated. In addition, it may be common for one to consider an agent as a point moving through a space during the simulation stage. In reality, the agent cannot be considered to be a point in space.These aspects of reality could potentially hinder one from achieving the desired results. Taking the physical dimensions of its body into consideration is one way to counter this.

In the above mentioned case of path planning, noise points were first removed using median filters from the raw map. Also, in order to introduce a safety margin, (and to compensate for the loss of information introduced due to blind spots as well as due to the resolution parameter) the detected obstacles were inflated by exaggerating their size. The safety margin could also be expanded to account for the dimensions of the robot body, thus ensuring a smoother transition from simulation to reality, without having to explicitly encode the details of the body geometry during simulation, thereby saving considerable development time. It should be noted that excessive expansion of obstacles could lead to failure of A-star to find a valid path to the goal.

Noise, and mismatches between virtual and real environments is inevitable. Noise removal using appropriate filters, and compensating for mismatches with the real world by erring on the side of caution may be considered to be useful measures to ensure a smooth transition from virtual to real environments.

V. Conclusion

This paper discussed solution strategies to address a set of common problems which may be encountered while adapting a low-cost robotics platform such as the EvoBot for research. Some insights into the factors to be considered while choosing the sensing, control and communication capabilities of low-cost platforms were discussed. The eventual success of our approach was described in the context of four diverse yet common robotics tasks - state estimation, real-time control, a basic swarm consensus application and a path planning task that were carried out using the EvoBots platform.

Some of the potential issues faced by end users who are not familiar with real-world implementation of algorithms are also discussed and potential work-arounds for a smooth transition from simulation to reality were suggested. The points discussed in this paper aim to serve as a guide to groups who intend to adapt similar low-cost platforms in the future, as well as to researchers working on theoretical aspects of robotics, who intend to validate their algorithms through real-world implementation.

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Improvements and considerations related to human-robot interaction in the design of a new version of the robotic head Muecas

Felipe Cid[1], Luis J. Manso[2] and Pedro Núñez[2]

***Abstract*— In this article the different decision-making that were followed in the design of the expressive robotic head Muecas are explained. Muecas is a system with a human-caricatured shape, equipped with a pair of robotic eyes, eyebrows, neck and mouth. The main goal in the design was to provide the robot with basic skills for an affective human-robot interaction, where the emphaty and attention plays an important factor. When developing this robotic head, it was necessary to study a number of parameters and characteristics related to human anatomy and psychology, as well as other similar robotic heads or the opinions of experts. All the results of these study are pointed out in this paper. Throughout this work, the step followed in the design in conjuction with the main conclusions drawn from it, are explained. We want that our work helps researchers in this field in their decision making.**

I. INTRODUCTION

The development of robotic platforms with anthropomorphic forms is an area of interest within the social robotics during recent decades. This is due to the rise of the algorithms based on the recognition of emotions, objects and manipulation algorithms based on robotic hands. Within this topic, the use of natural language in robotics is presented as a basis for improving the interaction with the people. Being the primary motivation for the development of systems capable of recognizing and imitating not only the emotions, but also the behavior. Therefore, it is necessary an evolution of the current systems and robots, to remain in the field of human robot interaction.

The current robotic heads are presented as platforms developed directly for the acquisition of information from the environment or objects, by means of systems that use movement or actions similar to the human. However, these heads tend to possess physiological characteristics similar to the human, which allows them to improve the interaction by means of multiple modalities of communication based on natural language. In the social robots, these physiological characteristics related to the anthropomorphism [1], allow the development of systems of recognition and imitation based on different modalities of communication, such as: facial expressions, speech and body language. Therefore, these modalities are a constant source of information on the emotions and intentions of the users in the communication, either through methods that acquire characteristics from a mesh model that analyzes the facial deformations [2], the changes in the prosody of the voice [3] or a model that tracks changes in the skeleton of the user [4].

The main contribution of this work is related to an extension of the publication that describes in detail the robotic head Muecas in [3]. This extension has as objective to describe the changes that are being carried out to develop a second version of the robotic head that consider aspects of different areas of the sciences, such as: psychology, mechanics, robotics, the morphology and the anthropomorphism. Despite the importance of functionality or external appearance of the robot, there are other theories that support the design of robots based on the different processes of learning [5] or action that will be a platform. These designs have as objective to improve the exchange of information [6], empathy with the user [7], and increase the number of possible actions with certain elements of the environment.

This paper is organized as follows: After discussing previous works in the literature related to design of robotic heads., in Section II. In the Section III, presents an overview of the improvements and considerations to take into account in the robotic head Muecas. Next, Section IV described the new mobile elements, degrees of freedom and facial expressions. In Section V, the multimodal systems are described, and finally, Section VI summarizes the conclusions and future works of the approach.

II. RELATED WORKS

The design of robots with human characteristics, so that they can communicate by means of natural language interaction is an area in constant progress. Currently the development of robotic heads is based on the interaction of different modality, whether facial expressions, voice or visual messages or body language. However, the most well-known cases at the level of research are: iCub [8], kismet [9], ROMAN[10][11], KHH [12], WE-4RII [13], SAYA [14][15], Barthoc [16], among others.

In the development of robotic heads there are several works that describe the changes and improvements to older versions of a prototype or product. Examples of this are the robotic heads: Flobi [17], Barthoc, ROMAN, SAYA, among others. Where, ROMAN and Barthoc describe step by step evolution to achieve a similar appearance to the human, while, Flobi describes in detail the development of this platform to get an appearance caricatured and anthropomorphic.

In the design of the different platforms used for the interaction it is possible to analyze four different types of

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[1]Felipe Cid is with Institute of Electrical and Electronics, Universidad Austral de Chile, Independencia 460 Valdivia, Chile. felipe.cid@uach.cl

[2]Luis J. Manso and Pedro. Núñez are members of the Robotics and Artificial Vision Lab. Robolab Group, University of Extremadura, Spain. lmanso@unex.es; pnuntru@unex.es

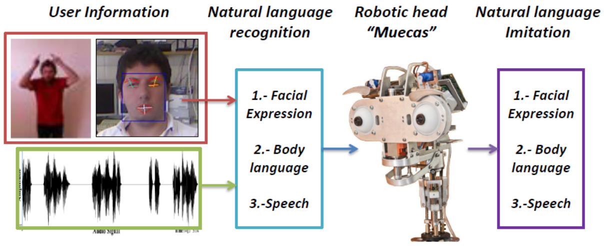
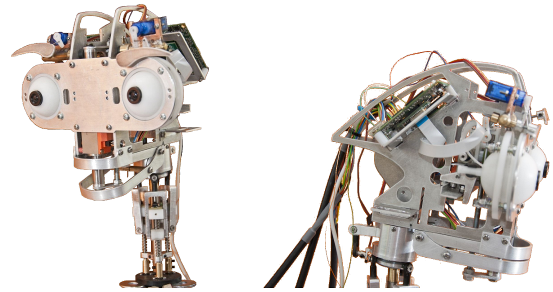


Fig. 1. Overview of the system of recognition and imitation of natural language by the robotic head Muecas.



(a) (b)

Fig. 2. Different perspectives of the robotic head Muecas

appearances, such as: Anthropomorphic, Zoomorphic, caricatured and Functional. Among these types of appearance, there are some that are designed to avoid the Uncanny Valley [18], creating another type of relations. For example, the Zoomorphic focuses on the natural relationship between an animal and a human. Meanwhile, the anthropomorphic appearances are looking for an advanced understanding by means of natural language. In the case of the robotic head Muecas was designed with a caricatured and anthropomorphic concept to support the interaction with young people, but keeping a bit of functional appearance. Finally, Table I shows a comparison of the different existing robotic heads and the head Muecas.

III. SYSTEM OVERVIEW

In this section, the design of a new version of the robotic head Muecas, is presented. The original version of this robotic head was published in [3], therefore, this work will be limited to explain some new improvements and considerations in order to improve the existing platform.

Muecas is a robotic head designed to study new methods of human-robot interaction based on natural language, through different modalities of communication, such as facial expressions, speech, body language, among others. For this reason, this platform uses multiple systems of recognition and imitation of natural language (See Figure 1), that take advantage of the 12 degrees of freedom to imitate the movement of the head in a similar manner to human, through elements such as: neck (four), mouth (one), eyes (three) and eyebrows (four). Besides, a series of sensors are used to acquire a large amount of visual, auditory, and depth information, being this information necessary for the systems of recognition and imitation. Figure 2 shows the robotic head Muecas from different perspectives.

The main aspects to consider in this new version would be associated with incorporation of new degrees of freedom through new mobile elements and the modification of existing ones. The most important changes are related to the elements, such as the eyelids, one degree more of freedom in the neck, new facial expressions and new covers to change the external appearance of the robot. The implementation of these changes, aims to improve the human-robot interaction through new movements and a change in the external appearance of the platform, but maintaining the anthropomorphic and caricatured concept which defines this robotic head.

Then it will describe describe the major consideration in the design, which hope to improve much interaction with users. Also, the technical considerations that will provide to the robotic head Muecas, qualities to represent a movement similar to a human.

- One of the first considerations would be the incorporation of new elements and degrees of freedom to the robotic head Muecas, in order to represent a body movement and behavior more similar to that of human beings by part of the robot.
- The implementation of more systems natural language recognition, through new modalities that deliver a better understanding of human communication. Since this robot only analyzes facial expressions and speech (voice and content), as explained in [3].
- The incorporation of learning processes to improve interactions uncontrolled in the implementation of tests, creation of database and algorithms based on Affordances [19].
- One factor to consider in this new design, it is the ability to integrate a localization system, by means of audio, vision, and depth (RGB-D). With this, it is expected that this robotic platform be able to locate the user to follow him with the cameras at all times, of form invariant to the obstacles or problems that may occur.
- The development of new facial expressions, due to the implementation of new mobile elements in the robotic head.
- One aspect to analyze is the integration of this robotic head in a humanoid robot or mobile platform, with emphasis on how it affects the interaction with the user. In addition, take into consideration the fact to take full advantage of the capabilities of the robotic head with respect to the main robot manipulator
- In order to avoid the Uncanny Valley [20], a humanlike appearance is maintained, but caricatured by covers with different designs. Meanwhile, maintains a similar movement to humans, but not identical.

In later sections these aspects will be analyzed one by one, explaining the improvements to be made in the current version of Muecas.

Robotic Head	Neck DoF	Eyebrow DoF	Eye DoF	Mouth DOF	FACS	Stereo Vision	Stereo Audio	RGBD Sensor	Inertial Sensor	Apperance
WE-4RII	4	8	3	5	yes	yes	yes	no	yes	Ant.
ROMAN	4	2	2	1	yes	yes	no	no	yes	Ant.
SAYA	3	no	2	1	yes	no	yes	no	yes	Ant.
KHH	4	no	3	no	no	yes	yes	no	yes	Tech.
BARTHOC	4	2	3	3	yes	yes	no	no	no	Ant.
iCub	3	LED	3	LED	no	yes	yes	no	yes	Ant.
ICAT	2	2	0	5	no	no	yes	no	no	Zoo
Muecas	4	4	3	1	yes	yes	yes	yes	yes	Ant.

TABLE I

COMPARISON OF DIFFERENT ROBOTIC HEADS IN THE LITERATURE (ANT.- ANTHROPOMORPHIC, TECH.- TECHNOMORPHIC , ZOO. - ZOOMORPHIC) (INFORMATION COLLECTED FROM: [3]).

IV. PROBLEMS IN THE CURRENT DESIGN

The old design of Muecas was presented as a platform with anthropomorphic features that was aimed at improving the empathy and naturalness of interactions with different types of users trained and untrained. However, the original design of the head contained many more elements than those described in the above publication [3]. An example of these missing elements are the same eyelids, given that Muecas has a oriented architecture for imitation of facial expressions, the absence of this mobile component is presented as an important gap. In this way, the eyelids are an important source of information related to the emotions of users in a interaction (mainly associated with the intensity of emotions) that allows us to integrate new facial expressions or emotional states, as described in the works of P. Ekman [21]. For this reason, in order to improve the functionality in different types of interactions, have been gradually integrated different aspects that were not incorporated or raised in the design, such as: mobile elements, multimodal recognition systems, new facial expressions, appearance, among others.

The changes in this new version considered some features that other similar robots possessed and some little analyzed trends in the current robotic. On the one hand, were designed new degrees of freedom associated with the neck and the eyelids, which allow to deliver more information through body language. The latter being an important factor, since the eyelids delivered much of the information related to the intensity of facial expressions. On the other hand, within the current robotic heads there are very few that are based on works from psychological studies, to support the possible facial expressions or the basic emotions that should generate a robot with anthropomorphic features. In this same way, we analyzed the possibility of changing the appearance of Muecas, with the objective to promote its appearance caricatured by means of covers. These covers allow the robot, the development of interactions closest and prevent manipulation of the mechanical elements by children.

This paper is divided into subsections that describe different aspects to consider in the design of new types of social anthropomorphic robots (See Figure 3).

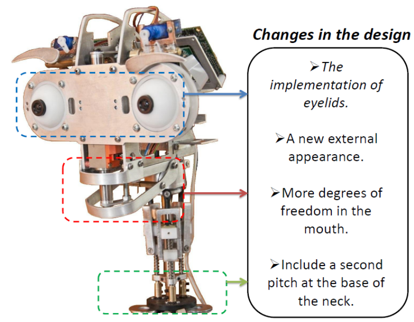


Fig. 3. Future changes in the design

A. Robotic eyelids

The eyelids are a major challenge in presenting a total change in the current structure of the eyes, since they need a minimum of two degrees of freedom to generate new facial expressions (See Figure 13). These degrees of freedom will be implemented through two servomotors HITEC HS-45HB (one in each eye), being the same motors used in the degrees of freedom of the eyebrows. This new movement related to the eyelids needs of a complex system that would allow an individual movement and synchronized movements in each eye, as shown in Figure 4. For this reason, it is developing a system responsible for moving the eyelids, through a mechanism based on folding layers covering the eyeball from the top to the bottom (See Figure 5(a)).

Within the literature, there are many works that demonstrate in practical ways that the eyelids are an essential part in the generation of facial expressions and the transmission of visual information [22][16]. However, in order to produce a greater degree of expressiveness and facial expressions more complex and realistic on the part of Muecas, is required of four degrees of freedom, as shown in Figure 5(b) and 6. These degrees of freedom allow generating a movement that the user perceives as similar to humans, which is necessary for the generation of facial expressions based on FACS [21] that classifies these movements (e.g. AU45 or AU46).

One of the main advantages in the implementation of the eyelids, is the ability to dramatically increase the emotional expressiveness of this platform. Due to that greater facial expressiveness is associated mainly with high levels of exci-

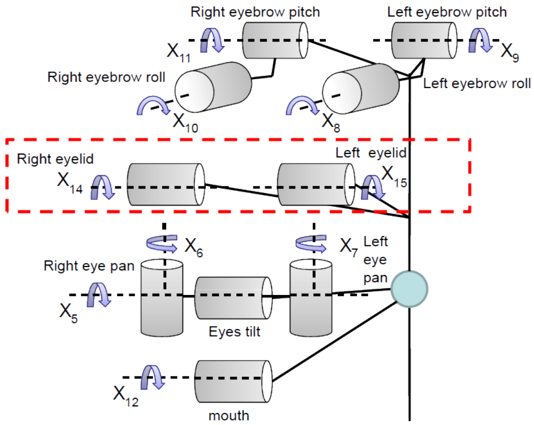
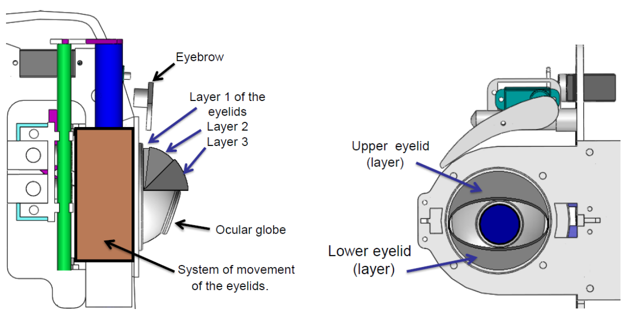


Fig. 4. Image of the degrees of freedom present in the eyelids.



(a) (b)

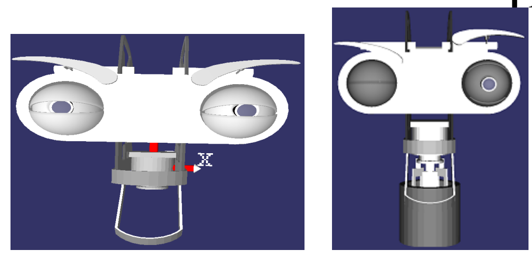
Fig. 5. Design of the system of movement of the eyelids.

tation in the emotions transmitted by the robot. Figure 6(a) shows an example of how the eyelids affect the perception of some facial expressions. Meanwhile, Figure 6(b) shows how the eyelids give the possibility to make some gestures typical of natural language as a simple Wink.

B. neck

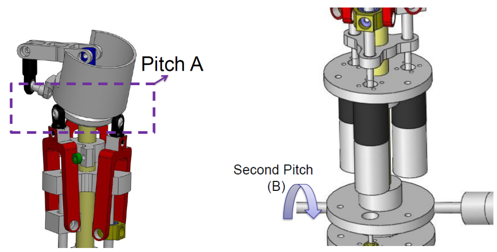
The neck of the robotic head Muecas is one of the more complex parts in the design and implemented these platforms. Since this element represents the key to the imitation of the movements of the human body language, introducing a system that recreates the movement of the human neck in such a way as to be recognizable movements by a user. However, these movement are generated in a different way to humans, which makes it possible to avoid the Uncanny Valley [18]. Because the design of this robot does not expect imitate identically human movements, but generate similar representations which are recognizable by users.

However, after a series of analyzes, it was decided to implement a movement missing on the base, known as a second pitch. This movement is basic in users, and allows a greater angle of inclination for the head that the first pitch. Figure 7(b) shows the implementation of this second Pich in a 3D model of the physical components of the neck, whereas in Figure 7(a) is shown the first pitch. In each of the mobile elements of the neck were used DC-micromotor 1724-024 SR (Encoder IE2-16 with 76:1 gear ratio), even in the new degree of freedom. Figure 8 shows the structure of



(a) (b)

Fig. 6. a) Example of the importance of the eyelids in the expressiveness of emotions of high arousal; and b) Example of a basic gesture of body language.



(a) (b)

Fig. 7. Design of degree of freedom related to the pitch.: a) Pitch A; and c) Pitch B.

the degrees of freedom in the existing robotic head, including the new degree of freedom associated with a second pitch. Finally, some examples of other platforms that implemented this movement, are: ROMAN [10][11], Barthoc [16], among others.

C. mouth

The mouth plays a significant role in how we perceive speech of an announcer in a conversation. This is due to the fact that much of the information, even auditory, requires a feedback through visual information. This is known as the McGurck effect [23]. However, the current design of robotic mouth does not allow a full perception of this effect. Given that this robotic mouth has only one degree of freedom, with the only function of opening and closing the mouth (See Figure 9(a)). For this reason, it has established the design of a robotic mouth that has the minimum capabilities of deformation, either in the opening, the contraction of the contours, and the extension of the lips forward (See Figure 9(b)). However, these movements are in development because they are a challenge to the current physical design.

Finally, it is important to mention that within most of the robotic heads, the incorporation of these mobile elements is not considered necessary, despite its importance in a communication based on auditory information.

D. External appearance

In the design of the robotic head Muecas, external appearance plays a crucial role to perform tasks of emotional interaction with users. For this reason, is not only is intended to catalog the appearance of the robot as anthropomorphic and caricatured, but develop a series of covers that allow experimenting with the human robot interaction.

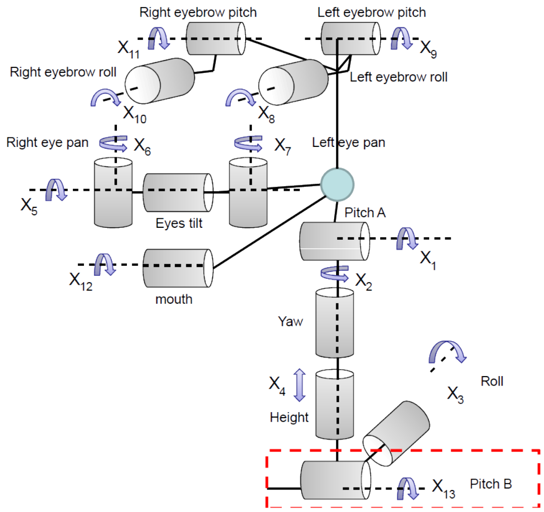
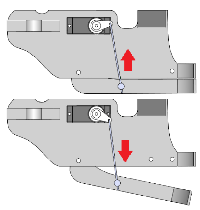
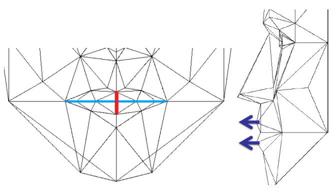


Fig. 8. Image of the degrees of freedom present in the neck, more the degrees of freedom associated to a second pitch in the base of support.

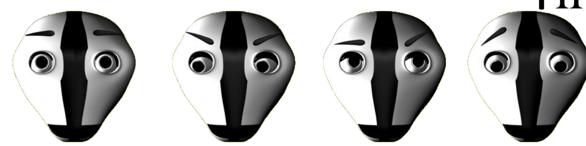


(a)

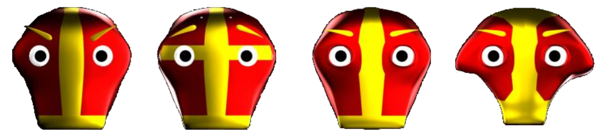


(b)

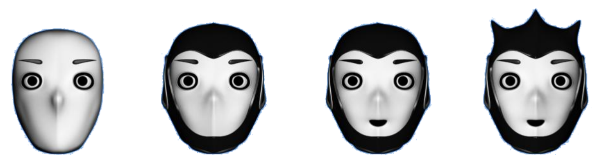
Fig. 9. a) Current robotic mouth of Muecas with a one degree of freedom; and B) Movements that should be emulated by Muecas, such as: contraction of the lip corners (blue), extension of the lips forward (purple), and the opening of the mouth (red).



(a)

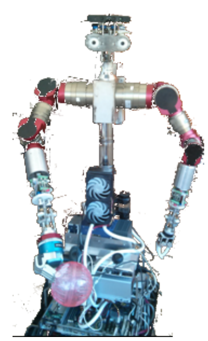


(b)

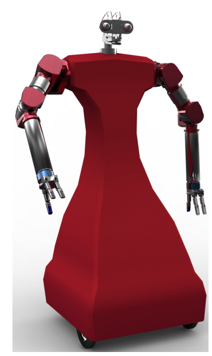


(c)

Fig. 10. Different prototypes of the cover for the robotic head Muecas.: a) First prototype of cover; b) Second prototype of cover. and c) Final prototype of cover.



(a)



(b)

Fig. 11. a) Current image of the robot Loki.; and b) 3D model of the new cover of the robot Loki. (Image (a) obtained from the publication: [19])

Figure 10 shows the covers designed for the robotic head Muecas through 3D models. The objective of these covers is to improve the level of empathy and care of people, mainly children, and bring them to a higher level of interaction without resorting to too many humanoid forms similar to the human that will lead us to the Uncanny Valley [18].For this reason, the choice of shapes similar to toys or cartoons seek to promote better interaction, as has been demonstrated in multiple works as: Kismet [9], Flobi [17], iCat [24], Probo [25], among others.

Currently, the autonomous robot Loki [26] has integrated the robotic head Muecas, in order to improve the user's response before a robot of large proportions. Figure 11(a) shows the robot Loki, and Figure 11(b) shows the cover ready to Loki. Given that this cover expects to achieve the same result that the prototypes described above, through an increase in the empathy and care in a user interaction with the robot.

E. New sensors and actuators

The original design of the robotic head Muecas possessed 12 degrees of freedom associated with a number of actuators that allow the movement of the neck (Pitch, Roll and Yaw), eyes (pitch and roll), eyebrows (Tilt and Pan), and mouth (aperture). Where is prioritized a natural movement that is identifiable as similar to humans but with a different kinematic. However, the constant interaction of this head with non-trained users and the general public, it allowed us to analyze the opinion of the user with regard to what elements are necessary to improve the current design. Thus, this feedback directed us toward a platform containing more mobile elements such as: eyelids, a second pitch, and more movements in the mouth. For this reason, new degrees of freedom need a series of actuators responsible for carrying out this function. Table II describes the current elements with the degrees of freedom, together to the new actuators and the degrees of freedom that are incorporated into this platform.

In the case of the sensors, this new version of Muecas only incorporates two microphones in the positions of the ears of the robotic head, in order to acquire auditory information for the development of tracking systems for users through the audio. Table III summarizes the current and new devices related to information visual, auditory and depth.

Element	DoF	Motors
Eyes	3	3 motors divided into 2x Faulhaber LM-1247 linear DC-servomotor (Pan) and 1 x Faulhaber LM-2070 lineal DC-servomotor (Tilt).
Eyebrows	4	4 HITEC HS-45HB servomotors
Neck	4**+1**	4**+1** DC-micromotor 1724-024 SR (Encoder IE2-16 with 76:1 gear ratio)
Mouth	1	1 HITEC HS-45HB servomotors.
Eyelids	**2**	**2** HITEC HS-45HB servomotors.

TABLE II

DESCRIPTION OF THE DIFFERENT DEGREES OF FREEDOM AND MOTORS OF THE ELEMENTS OF THE ROBOTIC HEAD MUECAS. (INFORMATION OBTAINED FROM: [3]).

Type	Sensors	Position
Stereo Vision	Two cameras Point Grey Dragonfly2 IEEE-1394	Eyes.
Stereo Audio Input	Two microphones connected to the pre-amplifier M-AUDIO MOBILEPRE USB	Sides of the head (ears).
Stereo Audio Output	Two speakers connected to the pre-amplifier M-AUDIO MOBILEPRE USB	Base of the head.
Inertial Sensor	PhidgetSpatial 1042–0 3/3/3	Back of the head.
RGBD Sensor	Microsoft Kinect Sensor or Xtion PRO LIVE Sensor (optional)	On the head.

TABLE III

DESCRIPTION OF THE DIFFERENT SENSORS OF THE ROBOTIC HEAD MUECAS. (INFORMATION OBTAINED FROM: [3]).

F. New Emotional States

The development of the human-robot interaction is present in the day to day, for this reason it is necessary to extend the capabilities of the current robots, in order to improve the skills of verbal, visual and emotional communication. With this objective, we carried out a study of the state of the art of the different theories about what are the basic emotions in human beings. The results of this study allowed for the selection of three theories of emotions studied and used in the robotics, such: the theory of Ekman [21], Russell [27] and Plutchik [28]. These three theories represent the basis for the choice of the emotional states with what will work the robotic head, which are: happiness, fear, sadness, anger and neutral. Where each emotional state is associated with a facial expression that will be recognized and imitated by the robotic head. Figure 12 shows these five emotional states with their respective facial expressions, which are performed by the user and imitated by Muecas.

In the Table IV shows the correspondence of the emotional states within the theories mentioned above. However, it is important to comment that the state $Neutral$ is a state not associated with any emotion, because it indicates the absence of a predominant emotion. In the same way, the state $Confused$ is presented as an emotional state necessary

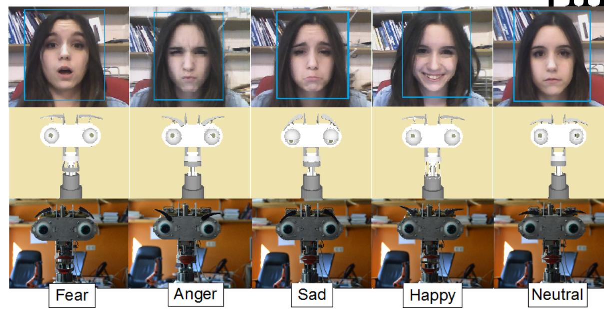
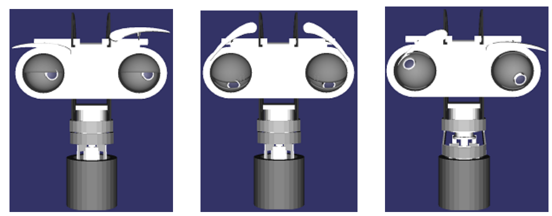


Fig. 12. Facial expressions recognized and imitated by the robotic head Muecas. (Image obtained from the publication [3])



(a) (b) (c)

Fig. 13. New facial expressions: a) Bored; b) Lonely; and c) Confused.

to present an idea or concept to the user, whether the information that delivery is not clear and it causes problems to the robot. With regard to emotional states in Table IV, it is important to mention that the names of some states may vary between emotional theories, for example: $Fear$ is $Afraid$ in the theory of $Russell$.

Emotional State	Ekman [21]	Russell [27]	Plutchik [28]
Sadness	x	x	x
Happiness	x	x	x
Fear	x	x	x
Anger	x	x	x
Neutral	–	–	–
Bored		x	x
Depressed		x	x
Confused	–	–	–

TABLE IV

EMOTIONAL STATES OF THE SYSTEM VS. THEORIES OF BASIC EMOTIONS IN THE FIELD OF PSYCHOLOGY.

These emotional states can be regarded as basic in the theories of the emotions, because they can be found in several works with different points of view, such as: Arnold [29], Frijda [30], Gray [31], Izard [32], James [33], McDougall [34], Oatley [35], Tomkins [36], among others. Where the emotions are classified by the inclusion criteria given by the author, as for example: Ekman considered a small group of universal emotions, Plutchik classifies the emotions with regard to adaptive biological processes, or Tomskins that considers the density of neuronal activity. (the reader can refer to some interesting works in [37]). Finally, Figure 13 shows the new emotional states through the simulator InnerModelSimulator of the framework RoboComp [38].

One aspect to take into consideration, in the case of the robots, is that the artificial facial expressions should be more exaggerated, to avoid any type of emotional confusion or ambiguity in communication. This is due to the fact that communication systems based on natural language have a limited amount of facial expressions, associated with the low number of actuators that generate movements in the elements of the face. In contrast, a human has a large amount of facial muscles that generate distortions studied and classified by systems, such as the FACS [21].

V. MULTIMODAL SYSTEM

The recognition systems of the robotic head Muecas [3], can be divided into two basic systems: Facial expressions and speech. However, in order to improve the system of recognition of emotions, and analyze the most of the information related to natural language, a module capable of analyzing the information of the body language through the depth sensor of Muecas has been integrated. This system analyzes a model of the human skeleton by extracting 7 features related to the movement, which allows to analyze the body language and estimate the emotional state of the user (more details in [4]). The output of this system provides information relating to the AUs for each element of a facial expression in the user. Thus, these AUs that are updated by each expression allow the robot not only recognize, if not also imitate these expressions in real time, in accordance with the relationship between the facial deformities and the movements of the mobile elements of Muecas (See Table V). These elements of the robotic platform include: eyebrows, eyelids, eyes and mouth.

Emotion	AUs	Mobile components of *Muecas*
Neutral	-	-
Happy	AU6-AU12-AU25	Eyebrows-Eyelids-Eyes-Mouth
Sad	AU1-AU4-AU15-AU17	Eyebrows-Eyelids-Eyes
Fear	AU1-AU4-AU20-AU25	Eyebrows-Eyelids-Mouth
Anger	AU4-AU7-AU17-AU23-AU24	Eyebrows-Eyelids

TABLE V

MOVEMENTS OF THE ROBOTIC HEAD *Muecas*, AND MOBILE ELEMENTS ASSOCIATED WITH EACH EMOTIONAL STATE (TABLE OBTAINED FROM THE PUBLICATION: [3]).

In the case of multimodal localization systems, it is working to integrate the tracking system of the model of mesh Candide-3 [2] with a localization system based on audio, as the submitted by [39].

A. Learning by imitation in robotic heads

One of the main attributes of the systems for recognition of emotions associated with this platform, is the property of self-training with the robotic head Muecas.This process uses TTS and ASR systems (explained in [3]), to generate a database of information of learning for a system of recognition of facial expressions based on Candide-3 [2], without the need for a supervisor or a third party during

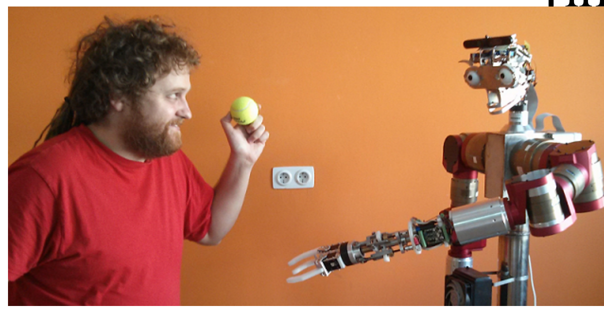


Fig. 14. The user interacts with the robot Loki and the robotic head Muecas

the experiment. Given that the conditions of the experiment are focused on improving the interaction, and that Muecas only has a limited amount of facial expressions associated with different emotional states, the process of imitation will provide of exaggerated facial expressions and specific for each emotion (See Table V) that will be recognized by the user.

This process of interaction, it is carried out by means of verbal messages, such as:

- Muecas: The test has begun, please express a facial expression.
- User: (The user performs a certain facial expression, trying to show a specific emotion)
- Muecas: (The robot, to recognize the facial expression of the user, imitates the expression through the movement of its mechanical components)
- User: (Evaluates the success/error in the recognition of facial expression)
- Repeat this sequence until complete the experiment.

Finally, this process is repeated for all emotional states required in 20 repetitions.

An example of systems of learning related to robotic head Muecas is [40]. In this case, we used Muecas to perform the interaction with the user, while acquires the emotional information of the user and about the objects in the environment. Given that this information from the user and the objects, are the basis for the use of affordances. Finally, Figure 14 shows an example of a complex interaction that includes facial expressions, and robotic manipulators.

VI. CONCLUSIONS

The robotic heads need a process of development and constant evolution, which will enable them to improve and adapt in a better way to users. Either through non-invasive methods, interactions based on the natural language or forms more user-friendly. Currently, the robotic heads do not incorporate certain fundamentals as psychological theories of the emotions or the effect McGurck that seek to support the compression of the human behavior through the analysis and observation. However, this work uses these theories related to emotions and how the human beings communicate to describe new aspects that are relevant to the design of anthropomorphic robotic heads, oriented to the human-robot interaction. Describing what are the enhancements and considerations that were obtained after working with the first version of Muecas.

In relation to other robotic heads, Muecas can be considered a robot designed for the human-robot interaction and the development of learning by imitation based on natural language. Due to the different types of aspects evaluated in this document, have as goal replicate the movement and emotions in a different way to humans, but that is easily recognizable by the user. On the one hand, this platform focuses on the systems to improve the interaction through behaviors and actions similar to the human based on learning by imitation. On the other hand, the hardware focuses on elements such as the movements of the neck and eyes that allow a user tracking by cameras (within the eyes), avoiding sudden movements or jumps by means of linear motors.

In this paper, one of the main topics that were evaluated was the incorporation of new degrees of freedom in elements, such as: neck, eyelids and mouth. Besides, the integration of tracking systems and a new external appearance based on covers, aim to improve the interaction through communication.

Future work is aimed at implementing the considerations described in this paper, through the integration of an evaluation process based on interaction with non-trained users in uncontrolled environments.

ACKNOWLEDGMENT

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Lessons from the Design and Testing of a Novel Spring Powered Passive Robot Joint

Joel Stephen Short[1], Aun Neow Poo[2], Chow Yin Lai[3], and Pey Yuen Tao[3], Marcelo H Ang Jr[2]

***Abstract*— The design, assembly, and testing of a new torsional spring joint for use in underactuated robots is presented. The joint can use an array of spring sizes and is able to adjust the spring offset and preload independently. This work outlines the design process with details on the troubles faced and lessons learned from multiple redesigns.**

I. INTRODUCTION

The design of new mechanical parts and assemblies is an integral part of robotics research. Even when an engineer's research is mainly theoretical, it is typically expected that the theory will be tested in an experimental setup, often requiring the design of specialized pieces and devices, either for testing by themselves or inclusion in a larger robotic setup. While there exist many design and testing methodologies for mechanical and mechatronic parts and assemblies, when seeking to create a one-off prototype there is normally not enough time for these long processes. The engineer must try to quickly design, build and test an assembly, being efficient and using only as much time as is necessary to ensure the design criteria is achieved. And this all must be done without running into dead ends or overly difficult problems during any stage of the build-up.

This work presents the design and build process of a torsional spring joint with a special emphasis on the problems encountered and the lessons learned. A short background sets the stage for a discussion of the design goals and the resulting initial design. Then the assembly and testing are discussed with a presentation of the problems, attempted solutions and final torsion joint layout. Lastly a discussion presents the key lessons learned from this experimental work and how they can contribute to prototype design in the future.

A. Background

While working on a stable system inversion method for the control of underactuated robots, a technique first investigated by [1] and expanded by [2], there arose a need for an underactuated robot, for testing of the method proposed in [3]. The motivation behind designing and building an underactuated robot was twofold, first it would provide a experimental platform to test the theoretical system inversion method mentioned above, and second, it would give insight into the general capabilities and usefulness of such a robot.

The robot is required to perform cyclic(repeating) tasks and is made up of two linkages in a planar arrangement. There is an actuator at the first joint and the torsional spring mechanism at the second joint, see Figure 1 for a simplified model of the robot. The actuator and passive joint placement ensures that the robot is underactuated but not completely uncontrollable, as backed up by the general serial-link robot analysis done in [4]. There are many reliable sources to use

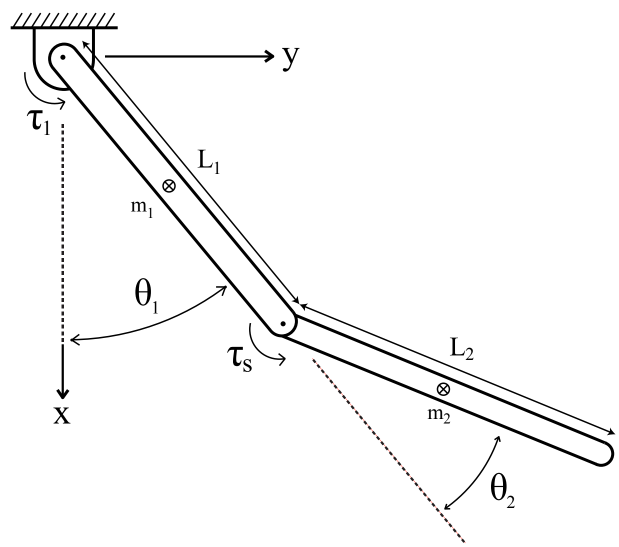

Fig. 1. 2DOF planar robot with torsional spring joint

when working with springs and mechanical design, though [5] was consulted most often for this project.

The use of torsion springs to provide a passive torque, that depends on the position and arrangement of the spring, is a very old idea and most easily seen in the common clothespin, yet its use in robotics has been limited. An early study of torsional springs within the dynamics of the a generalized robot framework can be seen in [6]. Other closely related work focuses on using springs in conjunction with actuators, normally classified as passive-compliant or variable stiffness actuators. A useful survey of various passive-compliant actuators, where the springs basic properties are used without

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[1]Joel Stephen Short studies at the National University of Singapore and also a student member of the SIMTech-NUS Joint Lab (Industrial Robotics), c/o Department of Mechanical Engineering, National University of Singapore, 9 Engineering Dr. 1, Singapore 117576 joel.stephen.short@u.nus.edu

[2]Aun Neow Poo and Marcelo H Ang Jr are with the Department of Mechanical Engineering, National University of Singapore, 9 Engineering Dr. 1, Singapore 117576 and also staff members of the SIMTech-NUS Joint Lab (Industrial Robotics) mpepooan@nus.edu.sg; mpeangh@nus.edu.sg;

[3]Lai Chow Yin and Tao Pey Yuen are with the Singapore Institute of Manufacturing Technology, Agency for Science, Technology and Research, Singapore 638075 and also a staff member of the SIMTech-NUS Joint Lab (Industrial Robotics), cylai@SIMTech.a-star.edu.sg; pytao@SIMTech.a-start.edu.sg

adjustment, is seen in [7]. Some variable stiffness actuators use actively adjusted springs, as seen in [8], showing an additional connection to biomechanical design.

The design presented here is unique in two ways; first it is very versatile, capable of using many different size springs, second, it is highly adjustable, allowing the offset and preload to be set independently. Though experimental, this joint allows for greater investigation into the capabilities and usefulness of torsional springs within the serial-link robot framework.

II. Design

The design of the torsional joint was performed using the traditional tools and methods of the mechanical engineer. After developing a few possible ideas that led to sketches and drawings, the most promising one was built up in a computer aided drafting (CAD) program (Autodesk Inventor) with the creation and virtual assembly of the parts. The completed initial design of the prototype led to the manufacturing and assembling of the parts. The build, test, and redesign cycle was run through twice with the final prototype showing reliable performance in all important areas of the design.

A. Design Goals

Adapting the basic spring principles and capabilities for use in a torsional spring driven joint started with a review of what was needed from the joint. The design goals were created by reviewing the needs of the overall robot as well as the materials and space available. The goals are built around keeping the design simple and are listed below:

1) Use a single torsion spring
2) Offset and preload angles must be adjustable
3) Spring body width must be adjustable
4) Only use the spring in compression
5) Allow an optical encoder to read the angular position

The experimental nature of the joint drove the first and second goals, to allow for adjustment of the spring position and initial torque. The use of different springs prompted the third goal. The fourth design goal was created after investigating the proper use of torsional springs, they are not made to be used repetitively in both tension and compression. Most manufactures recommend only using them in compression. The last goal is due to the experimental nature of the mechanism and enables the angular position feedback from the joint to be recorded, allowing further study and evaluation of the robots motion in post processing.

B. Implementation

The simplest and most direct design uses only one spring and two pairs of hook and flange subassemblies. Each hook plate is attached to a flange that is stacked with another flange with both secured to the robot linkage. There are two flanges per link, one set has long flange arms and the other short flange arms. This hook hand-off design, with the two different flange arm lengths, ensures that the torsion spring is only used in compression, no matter if the linkage moves in the positive or negative radial direction.

The flanges can be rotated independently, along the chamfered slots, when the screws are loosened as seen in Figure 2. The flange slots allow both the preload and offset of the spring to be adjusted within a limited range of positions. The range of motion and possible adjustment is outlined in Table I while the setting ranges of the offset and preload are shown in more detail in Figure 3. The graph helps show that as the offset is adjusted the available offset range also changes, this is due to the limits of the mechanical setup.

The spring sits around the joint axle with the second link mounted to the axle using a mini-bush clamp, this allows the linkage to be placed higher or lower on the axle depending on the size of spring used. The axle is secured to the first joint with a single ball bearing.

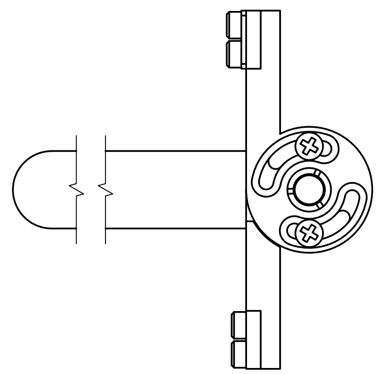


Fig. 2. Linkage 2 flange attachments

The last design goal, allowing an encoder to read the angular position, was fulfilled by creating a joint axle with a small protruding extension at the bottom. An encoder could then be mounted on the underside joint, specifically on the end cap spacer, with the optical wheel mounted at the end of the axle.

TABLE I
TORSIONAL SPRING JOINT PROPERTIES

Parameter	Stiffness	Offset	Preload	Link 2 Motion
Variable	k	θ_f	θ_p	θ_2
Range	$(0.02, .01)$	± 50	$(-20, +80)$	$(-175, +270)$
Units	Nm/rad	$degree$	$degree$	$degree$

The overall design can be seen in Figure 4 with its related parts list in Figure 5. All of the design goals were achieved in the general design layout, though only by building the torsional joint and testing it could the mechanism be deemed successful.

III. Assembly and Testing

The prototype went through a cycle of assembly, testing, and redesign, twice before the arriving at the final setup. Therefor are three designs, denoted alpha(original), beta, and final. The difficulties encountered at each stage are discussed leading to the proposed solutions and redesign.

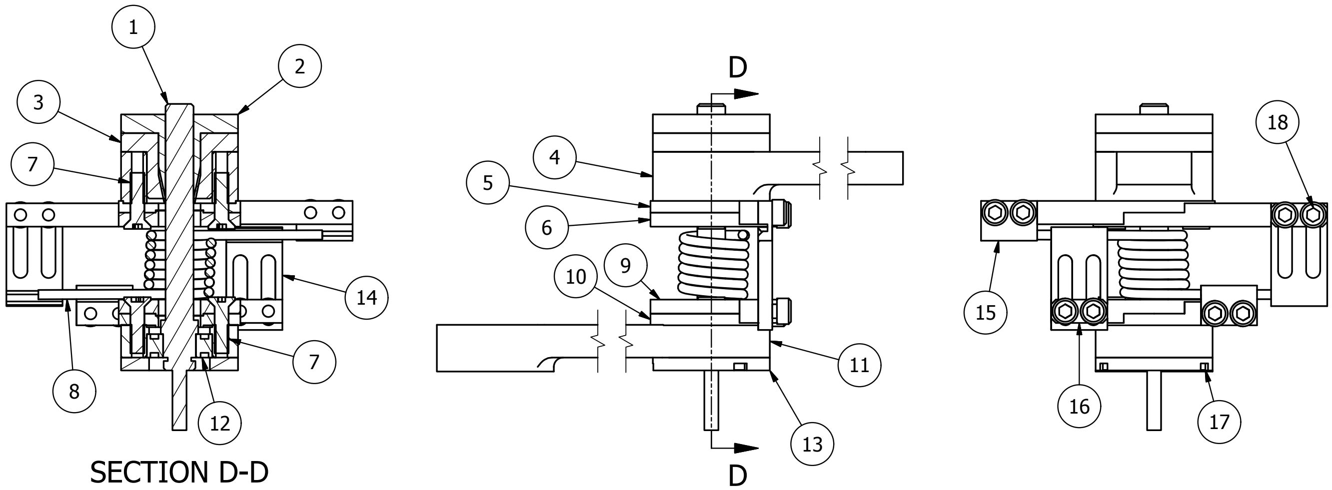


Fig. 4. Overall design of the torsional joint, optical encoder to be mounted at the joint underside, to linkage 1

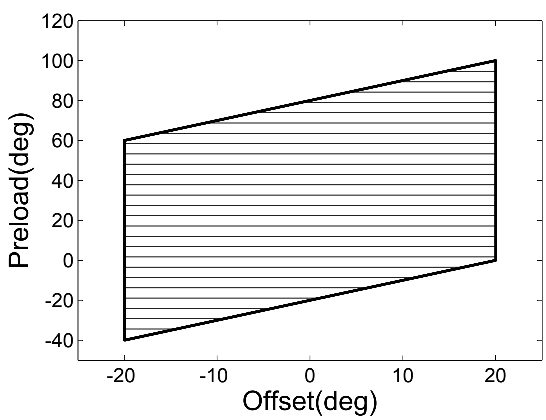


Fig. 3. Range of Torsion joint settings

PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Joint 2 Axle
2	1	Mini-Bush Inner
3	1	Mini-Bush Outer
4	1	Linkage 2
5	1	Upper Flange2
6	1	Upper Flange1
7	4	M3x10 CSK
8	1	Torsion Spring
9	1	Lower Flange1
10	1	Lower Flange2
11	1	Linkage 1
12	1	Ball Bearing
13	1	End Cap Spacer
14	2	Long Hook
15	2	Short Hook
16	2	Washer Plate
17	3	M2x6
18	8	M3x6

Fig. 5. Torsion joint parts list

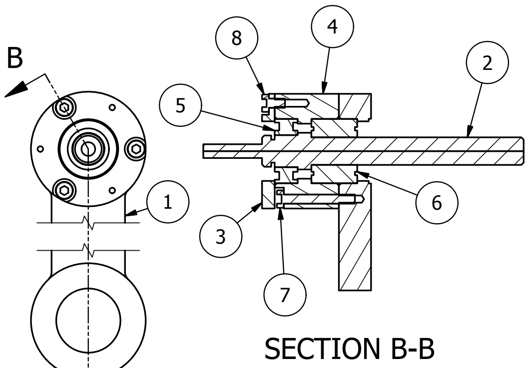
A. Alpha results

The parts for the torsional spring joint were sent out for manufacture at a local machine shop while the mini-bush, springs, and hardware(bolts) were procured from local suppliers. Upon receiving the parts and assembling the joint a major problem was observed; the bore in linkage 1, to house the ball bearing was cut 1mm to short, causing the bearing to protrude from the housing. This was discouraging but before sending the part back to be finished properly, the rest of the assembly was constructed to check for other problems.

Additional investigation proceeded despite the improper fit of the bearing and another major problem was found. The ball bearing tolerances were far too loose and allowed the axle to wobble from side to side. This caused the hook hand-off to sometimes miss and more importantly the optical encoder could not function reliably under such wide tolerances. After considering this major problem of axle wobble, it was thought that by adding a roller bearing to the axle the problem could be fixed with the addition of only one new machined part, an extension spacer. All the original parts could still be used. This new design compensated for the previous machining error, a drawing of the new bearing package can be seen in Figure 6. The tolerance limit of the encoder was closely consulted but due to the lack of precise bearing tolerances from the manufacturer the redesign had to rely on the best estimates of the engineer.

Lastly, as part of the hook hand-off difficulties, the short hook trough (where the spring sits on the hook) was found to be too close to the flange, making it difficult for the long hook plate to grab the spring leg at the hand-off. The new hooks would be needed to allow for easy transition, a comparison of the old and new hooks is seen in Figure 7.

The hook plates lacked specific angular markings, so preload and offset angles had to be estimated. In order to change out the torsion spring or adjust the preload or offset the second linkage had to be removed from its axle. This was not difficult due to the locking mini-bushings used, though



PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Linkage 1 V2
2	1	Joint 2 Axle V1
3	1	End Cap Spacer
4	1	Extension Spacer
5	1	Ball Bearing
6	1	Roller Bearing
7	3	M2x15
8	3	M2x7

Fig. 6. Second torsion joint design (Beta)

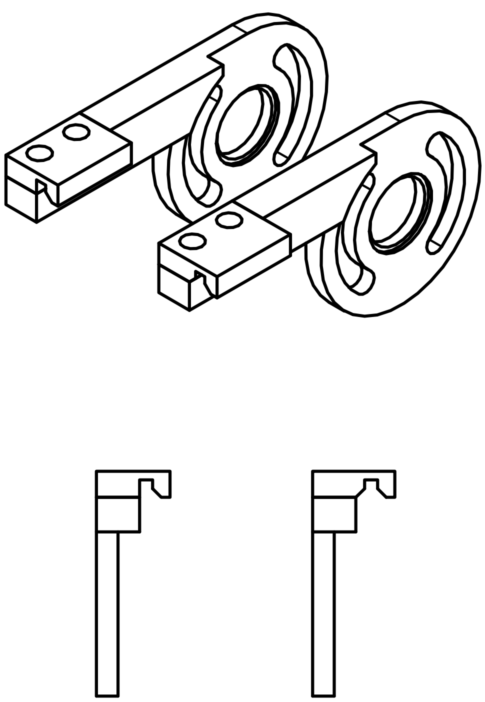
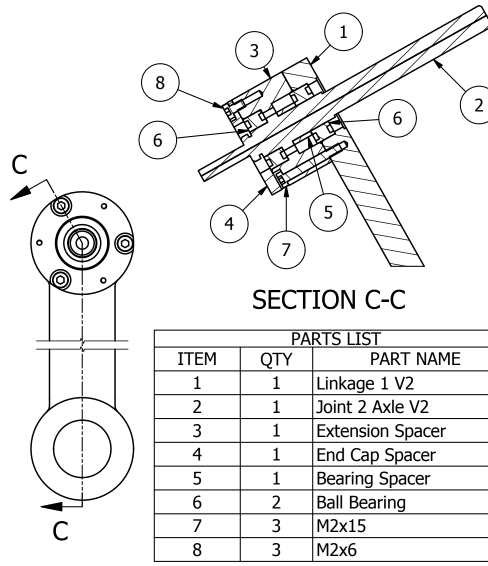


Fig. 7. Old hook (left) with new hook (right)



PARTS LIST		
ITEM	QTY	PART NAME
1	1	Linkage 1 V2
2	1	Joint 2 Axle V2
3	1	Extension Spacer
4	1	End Cap Spacer
5	1	Bearing Spacer
6	2	Ball Bearing
7	3	M2x15
8	3	M2x6

Fig. 8. Final bearing package

it made adjustments a tedious affair.

B. Beta results

With an additional roller bearing, a new short hook, and the extension spacer the second assembly proved to still contain difficulties. The new short hook allowed the hook hand-off to proceed smoothly despite the fact that the joint axle wobble was still too great. The roller bearing did reduce the axial play (in terms of the wobbling) but not enough to allow for reliable readings from the optical encoder mounted on the bottom. It was at this point decided that an adjustable bearing package would be the best solution, then the tolerances of the ball bearings would not be an issue. The final bearing setup is seen in Figure 8.

The final design required a new joint axle that was slightly longer as well as a bearing spacer for the axle. An additional ball bearing was also needed. The measurements sent to the machine shop, regarding the bearing package, were kept rough such that upon assembly the engineer could adjust the fit of the bearing package to allow an appropriate amount of play. If the bearings package is too tight and the axle won't turn, the bearing spacer can be ground down, while if the package is too loose, the machined surface of the extension spacer (which sits against linkage 1) can be ground down. This is a common method for tuning the bearing clearances of large gearboxes.

C. Final results

The final build-up of the torsional joint can be seen in Figure 9. The tuning of the bearing package was done by hand; by using a hand file and a lathe the extension spacer was ground down progressively, bringing the outer races of the bearings closer together until the axle wobble was eliminated, but it could still freely turn.

The final design was completely successful in achieving all of the design goals. The optical encoder returned a reliable signal while the adjustability of the joint allowed for the use of different springs and numerous different offset and preload setups.

IV. DISCUSSION

The design, assembly and testing of the torsional joint was completed as a prototype, for use in testing a theoretical control methodology and some important lessons can be learned from the process. The failures in design and the route taken in redesigns reveals some beneficial as well as detrimental decisions. These will each be discussed as they relate to either the design of the mechanism or the testing of the assembled parts.

A. Design Lessons

Lesson 1: Bring all the design constraints together, explicitly listing how they need to be achieved.

The design goals of a mechatronic system typically involve requirements from the mechanical side, such as bearings, fits and hardware, as well as from electrical parts, such as encoders, motors and other interface pieces. If details are left out, they will often show up as trouble during testing. The design goals in the example were clear when the mechanism was first drawn up, the needs of the torsional spring adjustments were straightforward to implement, but the optical encoder requirements were not explicitly checked in the initial design. This lack of detail in the design goal contributed to the problems found in the first design, leading the the first redesign.

Lesson 2: The simplest solution is not always the best, choose the redesign solution that solves the problem most completely.

When redesigning a part or assembly, the simplest and most minimal design is often the most attractive but when considering the complexity of the possible solutions, go with the one most likely to solve the problem, even if it is more complex. The first redesign of the bearing setup only required one more machined part and one additional bearing, plus it allowed the imperfection of the bearing bore in linkage 1 to be left alone. It was thought to be the most economical, yet there was little to no guarantee that it would solve the axle wobble problem. The adjustable bearing package was slightly more complex but should have been used in the first redesign.

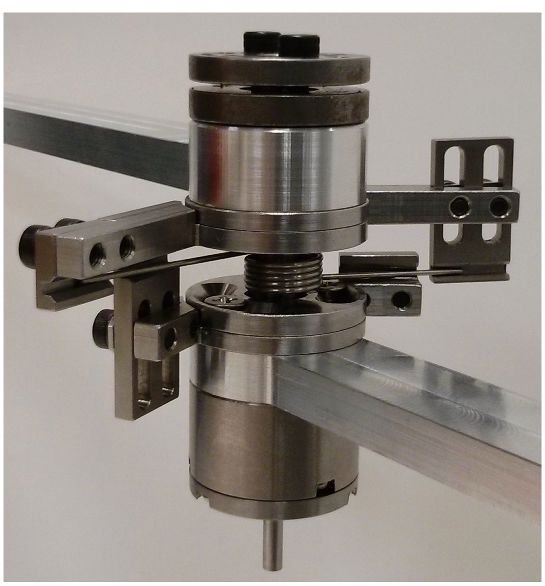


Fig. 9. Final torsional joint setup (without encoder)

Lesson 3: Familiarity with standard engineering solutions that are related to the current design is highly beneficial.

The design of a prototype lends itself to quick thinking and the use of engineering solutions that "may" work or "should" work. Though time is often of the essence and there is not time for an in depth analysis of the parts to ascertain if the part or assembly will meet the design goals exactly it is critical that the engineer have a general understanding of standard industry and engineering practices. Spending time to become familiar with the traditional solutions, relating to the particular parts or assemblies under design, can save time and energy later in the process. This can be readily seen in the example when considering the bearing setup for the joint axle. The first design turned out to be inadequate and only a half measure. Instead, the industry standard for bearing packages which need tight tolerances should have been used right away.

B. Testing Lessions

Lesson 4: Test and investigate all aspects of a mechanisms design, as able, before disassembly and redesign.

When working with the design, assembly and testing of prototype, it is important not to get caught up with a single problem such that it distracts from overall testing. This is seen with regards to the machining mistake on the first linkage, where the bearing bore was to short. Instead of immediately sending the part back for correction and having to wait before testing the overall mechanism, the engineer assembled the rest of the parts to examine the part interfaces, the hook hand-off. This additional testing revealed problems that were much more critical than the bore mistake. By testing and examining the assembly as much as possible before trying to fix the small mistake, time was saved and the redesign could include the altered dimensions.

Lesson 5: Implement low risk redesigns early.

Lastly, when working with and testing an assembly of parts that requires a redesign, take time to step back and examine the assembly as a whole, looking for small problems that can be improved with a low risk of affecting the overall working of the mechanism. Including these improvements in a first redesign can save time in later testing. An example of this is seen in the short hook redesign. Though the wobble of the joint axle, when supported by one ball bearing, contributed to an unreliable hook hand-off the engineer was able to identify a second problem area around the short hook. The hook trough was too close to the flange, in order for a successful spring leg hand-off the long hook was required to pass extremely close to the short hook flange. The hook was redesigned to allow for more space between the moving parts. This contributed to a smoother working hook hand-off of the spring, outside of the troubles with the bearings.

V. CONCLUSIONS

When designing, building and testing a prototype mechanism for robotics research there are often difficulties. The short time schedule forces an engineer to make certain assumptions and estimations, which can lead to trouble in the assembly and testing phase. This paper presented the experience of one researcher in designing, building and testing a torsional spring joint prototype. The process faced a few problems but through two redesigns the failures were solved, producing a successful mechanism that met all the required design goals. The lessons learned from this process were discussed in detail and connected to specific examples in the design and testing of the torsional spring joint.

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Design, Simulation and Implementation of a 3-PUU Parallel Mechanism for a Macro/mini Manipulator

Zheng Ma, Aun-Neow Poo, Marcelo H. Ang Jr , Geok-Soon Hong, and Feng Huo,

Abstract— **Parallel mechanisms have the advantages of high rigidity, high precision and fast movement in its workspace. It is a most suitable mechanism to serve as the mini manipulator in a macro/mini manipulator as the mini manipulator needs to have fast response and high resolution in positioning. In this paper, the design of a 3-PUU parallel mechanism to be used as such a mini is presented. Failures are encountered during the process of simulation and implementation of the parallel mechanism. Causes of the failures are analyzed and solutions are proposed to overcome these. Based on the lessons from building the first prototype, improvements were made to the second prototype which effectively removed the shortcomings resulting in a mini which met the requirements for its intended application.**

I. Introduction

The development and application of robotics has made much progress since the first programmable industrial robotic arm, the Unimate, was invented in 1961. Compared with human operators, industrial robots have the advantages of high precision, repeatability and speed of motion, and high dexterity. They can also work in environments hazardous or unsuitable for human beings and, with large robots, are capable of carrying and moving, with higher speeds and accuracy of motion, heavy workpieces. In addition, except for downtime for maintenance, they are 24/7 workers who do not need rest or holiday leaves and can thus improve productivity and speed of production.

When used appropriately, industrial robots can reduce the need, not only of unskilled labourers but also skilled workers, in industry. As a result, they have found widespread applications in repetitive operations such as material handling and assembly, welding and spray painting. To date, most of the applications of industrial robots are for non-continuous contact type of operations, operations which do not require the robotic end-effector to be in continuous contact, and with a controlled level of contact force, with the workpieces.

Recent advances in robotics technology have allowed the development of robotic arms with increased speeds and precision of motion and with greater build-in intelligence. There is now increasing interest in developing and employing these devices for more challenging tasks, including those labour-intensive and low-productivity operations which involved continuous contact between the robot end-effector and the workpiece, and the simultaneous control of the force at the point of contact. Such force/position controlled operations include high-precision edge and surface finishing operations often encountered in the precision engineering, aerospace, and marine industries.

Since an adequate workspace and a sufficient payload-carrying capacity are required in the performance of their tasks, industrial robots are often designed with long and large arms. With its large mass and inertia [1], it is thus difficult to control such a single robotic arm in applications which require position, force or force/position control and achieve high accuracy with a fast response simultaneously.

A proposed solution is to implement a compact end-effector with a small limited workspace which can have a high bandwidth and high accuracy in positioning and have this carried by a larger but slower robotic arm. This configuration is commonly referred as a macro/mini manipulator, where the large robotic arm is referred to as the “macro”, and the smaller and faster end-effector referred to as the “mini”. The macro/mini manipulator has the advantages of a large workspace provided by the macro robotic arm, as well as a fast and high-accuracy response provided by the mini [2].

Considerations which need to be taken in the design of a mini manipulator depend on what tasks it is being developed for. In this paper, a mini manipulator designed for polishing and deburring tasks is discussed. The normal forces that need to be applied by the polishing or deburring tool on the workpiece are estimated at up to 100N and a few Newtons for polishing and deburring respectively. The optimum exerted force depends on the type of operation, the material of the workpiece and the type of tool used. A rough sanding/polishing operation using a sanding/polishing pad which has a large area of contact with the workpiece surface will require a large exerted force whereas a small exerted force will be needed for a fine finishing operation with a smaller polishing pad.

The profile of the surface of the workpiece that is to be operated on is assumed not to have sudden rapid changes such that a workspace in the form of a sphere with a diameter of 40mm will be sufficient for the mini end-effector. During a polishing or deburring operation, the macro manipulator carries the mini manipulator (end-effector) along a desired reference path parallel to and at a small distance away from the surface to be polished or from the edge of the workpiece to be deburred. For optimum operation, the orientation of the end-effector should have a predefined orientation with respect to the surface, or edge, of the workpiece. While being moved along this reference path by the macro, the mini moves in such

*Research supported by SIMTech-NUS Joint Laboratory and A*STAR.
Zheng Ma is with the Advanced Robotics Center and the SIMTech-NUS Joint Laboratory (Industrial Robotics), National University of Singapore, Singapore, 117580. (Corresponding author. Phone: +65-91188562; Email: mpemz@nus.edu.sg).
Aun-Neow Poo, Marcelo H. Ang Jr, Geok-Soon Hong and Feng Huo are with the Department of Mechanical Engineering, National University of Singapore, Singapore, 117576. (Emails: mpepooan@nus.edu.sg, mpeangh@nus.edu.sg, mpehgs@nus.edu.sg and huofeng@nus.edu.sg).

a way as to exert the desired normal force on the workpiece. Since the mini is always in contact with the surface or edge of the workpiece, and as long as there are no sudden and large change to the surface or edge of the workpiece, the workspace of the mini will not need to be large to perform the polishing or deburring task.

Based on the aforesaid considerations and using feedback from users with experience in polishing and deburring operations, a 3-DOF PUU(Prismatic-Universal-Universal) parallel mechanism, inspired by the Delta robot was selected for the mini manipulator. This 3-DOF translational parallel mechanism (TPM) has only pure translational motions and was designed to have a cylindrical workspace with a diameter of 40mm and a height of 30mm.

In the design process, solid models were first created to simulate and to analyze the motions, and to evaluate the stresses and deformations in the various links and components when it is subjected to the maximum design applied forces and torques. During the simulation study of its motions, unexpected motions with extra degrees of freedom were observed which caused the mini manipulator to take on postures in which the platform on the mini end-effector was not purely translated but was rotated from its starting position. A kinematic analysis based on the 3-DOF translational motion fails to explain these unexpected motions since the assumptions made in the kinematic analysis does not hold when the mechanism is not in parallel with its starting position.

To reduce the overall cost and time, the universal joint components are directly ordered off the shelf for implementation. The parallel mechanism appears to have notable backlash. The resulting precision of the mechanism is poor and cannot serve as the mini manipulator which supposed to have high accuracy in positioning.

The mechanism is modified eventually to overcome the backlash problem and retains the same kinematics as previously designed. As a result, the working range and mobility of the mechanism meets the requirement. Together with a proper control algorithm, the mechanism can be used to serve as the mini manipulator which has a fast response and high precession in positioning.

In this paper, the 3-PUU parallel mechanism is first described and a standard kinematic analysis is derived under assumptions. Unexpected motions in simulations are shown, with a brief analysis of the reason why it happens. Problems of backlash and positioning accuracy encountered in implementation is discussed with an analysis of an off-the-shelf universal joint structure. Improvements of the mechanism architecture and joint options are presented which overcomes the failure from the simulation as well as the real implementation.

II. Mechanism Description and Kinematic Analysis

A. A 3-PUU Parallel Mechanism

The structure of the 3-PUU parallel mechanism designed is shown in Fig. 1 with three identical limbs connecting the base platform to the top platform. Fig. 2 shows the structure for one of the limbs. From the figures, it can be noted that the three prismatic joints move in a direction perpendicular to the base platform and are attached symmetrically at 120 degrees apart at A_i, where $i = 1,2,3$, to the base platform. As shown in Fig. 1, two universal joints (universal joints) connect the end of each prismatic joint to the top platform. The axes of the two universal joints are parallel to each other and perpendicular to the prismatic joint. According to the Chebychev-Grübler–Kutzbach criterion [3], the number of degrees-of-freedom is given by:

$$M = 3(N-1-j) + \sum_{i=1}^{j} f_i \qquad (1)$$

where N is the total number of links, j the total number of joints, and f_i, ($i = 1,2,3$) the degrees of freedom of link i. For the mechanism shown in Fig. 1, the total number of links (including the base link) is $N = 8$, the total number of joints is $j = 9$, and the degree of freedom is $f_i = 1$ for the prismatic joints and $f_i = 2$ for the universal joints. Thus

$$M = 3(8-1-9) + 3\times 1 + 6\times 2 = 3 \qquad (2)$$

and the mechanism shown in Fig. 1 has three degrees-of-freedom with all being translational motions as will be elaborated on in the next section. This ensures that the top platform is always parallel to the base platform.

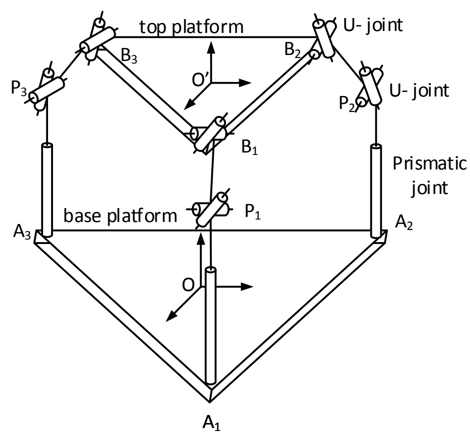

Figure 1. Structure of the 3-PUU parallel mechanism.

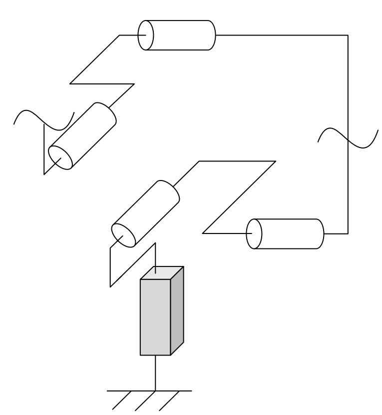

Figure 2. One of the limbs of the 3-PUU parallel mechanism.

B. Kinematic Analysis of 3-DOF Translational Motion

With knowledge of the 3-DOF translational mobility, the kinematic model of the parallel mechanism can be derived [4]. The top view of the base and top platform is shown in Fig. 3, where A_i and B_i are the locations where the prismatic joints and the universal joints are mounted to the base and the top platform respectively. Coordinate Frame O and Frame O’ are respectively attached at the centre of the base and the top platform. The distance from the center of the platforms to A_i and B_i are R and r respectively. Let the displacement of the i^{th} prismatic joint attached at A_i be z_i. All the universal joints are passive.

Since the parallel mechanism are constrained to have only translational motions, the transformation matrix for rotation from frame O’ to frame O is an identity matrix. Let the position vector of Frame O’ in Frame O be

$$[c]_O = (x \quad y \quad z)^T \tag{3}$$

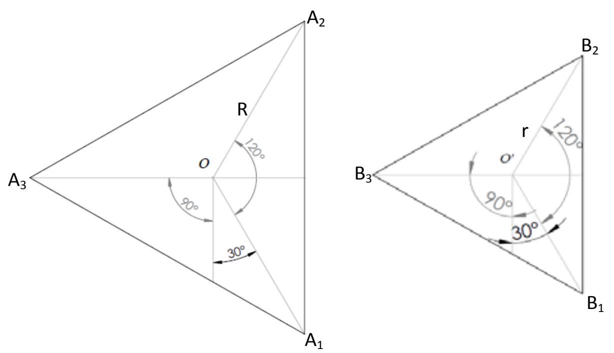

Figure 3. Top view of base platform(left) and top platform(right).

According to the mechanism structure shown in Fig. 1 and the geometric conditions shown in Fig. 3, the inverse and forward kinematics of the parallel mechanism can be obtained. By assuming the top platform has only translational motion with respect to the base platform, position vector B_i in frame O’ is

$$[B_i]_{O'} = (r\cos\theta_i \quad r\sin\theta_i \quad 0)^T, \quad \theta_1 = 30^\circ, \theta_2 = 150^\circ, \theta_3 = -90^\circ \tag{4}$$

Therefore the position vector B_i in frame O is

$$[B_i]_O = (r\cos\theta_i + x \quad r\sin\theta_i + y \quad z)^T \tag{5}$$

and the position vector P_i in frame O is

$$[P_i]_O = (R\cos\theta_i \quad R\sin\theta_i \quad z_i)^T \tag{6}$$

For all three limbs, if the distance between the two universal joints, B_i to P_i is L. The constraint equation can then be written as

$$\left\| [B_i - P_i]_O \right\| = L \tag{7}$$

After substituting B_i and P_i into (7), we have

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = L^2, \quad x_i = (R - r)\cos\theta_i, y_i = (R - r)\sin\theta_i \tag{8}$$

The inverse kinematics thus can be obtained as

$$z_i = \pm\sqrt{L^2 - (x - x_i)^2 - (y - y_i)^2} + z \tag{9}$$

In the same way, the forward kinematics can be obtained by applying the same constraint equation.

III. Failures in Simulation and Implementation

With the kinematic model obtained, the parameters R, r and L were chosen to meet the workspace criteria. Solid models were then established for motion and stress analysis, the former to confirm the translational motions of the top platform within the specified workspace and the latter for sizing the components for strength and stability.

During simulation, some unexpected results were observed when the top platform moved away from being parallel to the base platform. Unacceptable motion performance was also obtained with the first prototype developed using off-the-shelf universal joints. These will be discussed in the following sections.

A. Extra DOF observed in Simulation

Solid models of the parallel mechanism were created using the software SolidWorks®. Motion studies were done simulating motion at the three prismatic joints. This caused the three lower universal joints, P_1, P_2, and P_3 in Fig. 1, to move vertically. Various combinations of linear motions for the three prismatic joints were used to study the movement of the top platform relative to the base platform, as well as to verify the size of workspace of the parallel mechanism.

The top platform was expected to remain parallel to the base platform at all times since the design of the mechanism constrained it to have only 3-DOF translational motion. However, it was noted that for some motion combinations of the prismatic joints, the top platform does not always remain parallel to the base platform but moved into a non-parallel mode of motion after remaining parallel for some time. Fig. 4 shows an example of how the roll-pitch-yaw angles of Frame O’ with respect to Frame O change with time for one such instance. From the figure, it can be seen that the top platform moves with only translational motion for about 11s after which it has rotational motions.

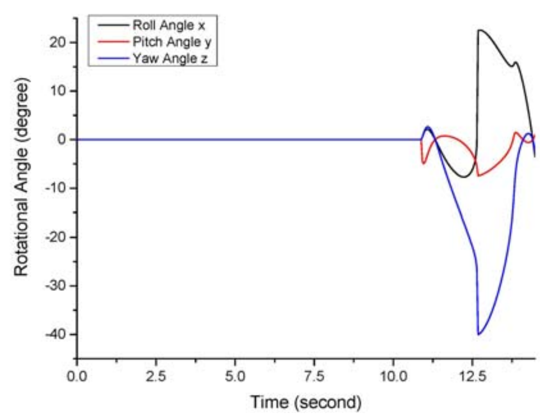

Figure 4. Roll-pitch-yaw angles oftop platform for non-paralle motion.

To explain the unexpected rotational motion, the assumption of pure translational motion was reviewed. A typical drawing of a universal joint is shown in Fig.5.

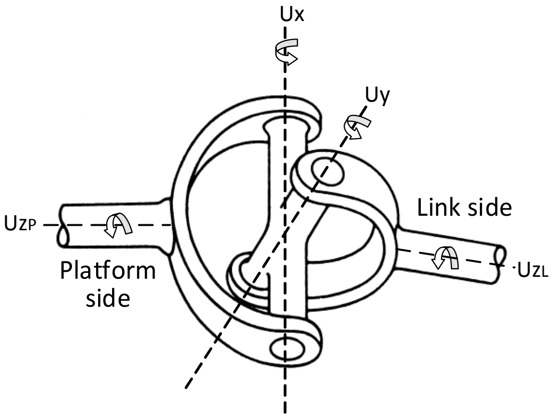

Figure 5. Rotational axis of a universal joint.

Consider one of the three universal joints attached to the top platform as shown in Fig. 5. With the other end, P_i, of the link fixed, there will be no rotation about the axis UZL, The universal joint can only rotate about the Ux and Uy axes, enabled by the cross component in the joint. With only two degrees-of-freedom, there will not be any rotation about the axis UZP, and thus no rotation of the platform [5].

Since there are three universal joints attached to the top platform, therefore no rotation of the platform is allowed about three axes. When these three axes are linearly independent in $\Re^3$, the top platform will lose all the rotational motion and its 3-DOF motions will be purely translational. Based on this analysis, the rotational motion of the top platform during simulation as shown in Fig. 4 is thus unexpected.

This rotational motion observed in simulation is suspected to be caused by the loss of independence among the three axes UZP*i*. When two or more axes become linearly dependent, the parallel mechanism will be in a singular position. Unlike the singularities in serial-link robots, instead of losing degrees of mobility, a parallel mechanism gains extra degrees of freedom at a singular position [6].

In Fig. 4, it is likely that the parallel mechanism reached a singular position at about 11s, gained an extra degree of rotational mobility and the top platform became non-parallel to the base platform. Thereafter, the motion of the mechanism was no longer constrained to be purely translational.

Referring to the Chebychev-Grübler–Kutzbach criterion, the mechanism should have three degrees-of-freedom when it is not in a singular position. It is likely that the motion of the mechanism after passing through the singular position is a combination of three degrees of motion with both rotation and translation. Further investigation will be needed explain and to understand this unexpected simulation result.

B. Backlash in Implementation

The universal joints used in the construction of the first prototype were off-the-shelf good quality joints the schematic of which is shown in Fig. 6. Each side of the universal joint has a hole to accommodate the external shaft and a dowel pin is used to hold the shaft to the joint as shown in the figure.

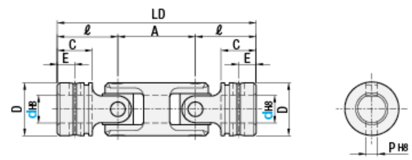

Figure 6. Universal joint(double) [7].

Figure 7 shows the first prototype of the mini manipulator mechanism using these universal joints. Three linear actuators, labeled with 0, 1 and 2, are used for the prismatic joints. Each link connecting the prismatic joint to the top platform is made up of a circular shaft with a universal joint at each end. The universal joint at one end of each link is fixed to a linear actuator and the other end to the top platform.

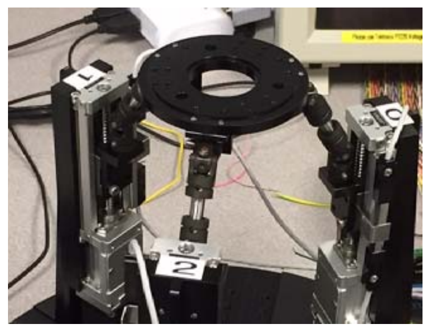

Figure 7. Translational parallel mechanism using U-joints.

When the three linear actuators are fixed in any position, i.e. not moving, the top platform should also remain in a fixed position parallel to the base platform. However, it was found that with the actuators fixed in their positions, the horizontal slack of the top platform was 4 to 5mm, which is unacceptably large, together with unacceptably large angular rotations. Investigations showed that these unacceptably large motions, or "backlash", are due to the clearances used in the manufacture of the mechanical components used. While pure translation motion of the top platform was observed in simulation for which perfect dimensions of the various components are used in computation, such perfectly formed parts are not available in practice, thereby resulting in the unacceptable results. A close examination of the first prototype showed that the exhibited backlash phenomenon is due almost entirely to clearances in the off-the-shelf universal joints used.

The universal joint, also known as a Hooke's joint, is a joint or coupling which is commonly used to transmit rotary motion from one rigid shaft to another rigid shaft when the axes of the two shafts are at a small angle to each other. The rotary motion transmitted is usually in one direction only. Because there is no change in direction of the transmitted rotary motion, the small clearances designed into them for ease of manufacture does not cause any backlash problem.

The universal joints used in the TPM mechanism in the work here serve a different purpose. They serve as joints providing two degrees of freedom (rotary motion) constraining the motion of the parallel mechanism as required from the structure shown in Fig. 1. Referring to Fig. 5, the universal joints used should rotate only about axes Ux and Uy to cause the top platform of the TPM mechanism to move. There should be no rotation about axis U_{zL} or U_{zP}. However, when one side of the U joint, say the link side, is fixed and not allow to rotate about its axis U_{zL}, it is observed that the other side has freedom to rotate, about axis U_{zP}, to some significant degree. This is due to manufacturing clearances designed into the joints, in particular at the four ends of the cross component in the joint. The resulting free-play or backlash is accentuated due to the short lengths of the two rods forming the cross component in the joint. The off-the-shelf U joints thus did not have sufficient stiffness along the Uz axes and are not suitable for the TPM mechanism.

Another significant cause of the free-play or backlash problem in the motion of the TPM mechanism is due to clearance applied during the fabrication of the mechanism. As mentioned earlier and with reference to Fig. 6, dowel pins were used to connect the external shaft to each end of the U joints. Ideally, the two holes in the U joint and the one in the shaft to accommodate the dowel pin should all be of exactly the same diameter, corresponding to the diameter of the dowel pin, with their centers perfectly aligned. However, as the holes were drilled at different times, if they were to be made of the same diameter with very little clearance, the centers of the holes need to be perfectly aligned in order for the dowel pin to be inserted. Alignment of the holes, when drilled separately, is not easily done. As such, the fabricator introduce some clearance and made the hole in the shaft larger (Fig. 8) than that of the holes in the U joint, which is of the same diameter as the dowel pin. While this allowed for the insertion of the dowel pin even if there is some slight misalignment of the holes during manufacture, it caused significant rotational free-play or backlash between shaft and the universal joint. Here again, the rotational backlash is accentuated by the small diameter of the shaft, and thus the length of the hole in it.

Figure 8. Clearamce between dowel pin and the external shaft connected to the U-joint.

The unsatisfactory motion of the first prototype of the mechanism is largely due to the clearances in the off-the-shelf universal joints and the limited machining accuracy of the fabricated parts. Information on clearances for off-the-shelf universal joints are not readily available from manufacturers as such information may not have been important when they are used for their typical functions of transmitting rotary motion between two shafts.

The first prototype failed to meet the requirements for its intended application and a review of the design, and where it failed, was carried out to come up with the second prototype.

IV. Learning From the Failures

In the process of developing and building the first prototype, two valuable lessons were learned. One is the unexpected results during simulation studies and the other is the poor performance in the fabricated mechanism due to manufacturing clearances and backlash in the off-the-shelf universal joints used.

It is noted that that the top platform of the mechanism does not remain parallel to the base platform under all circumstances. Rather, when starting from a parallel position, the top platform may move into a mode, or region of its workspace, where it gains rotational motions after passing through a singular position. This problem occurred during simulation when it is put all possible motions within its total workspace. In practice, this problem can easily be overcome by constraining the motions of the three actuators such that its workspace clearly does not contain any singular positions.

The first prototype has unacceptably poor accuracy in its motion and positioning. The top platform has some degrees of mobility, of about 5mm due to backlash when the actuators are fixed in their positions. This mobility is not acceptable as the mini manipulator is required to have high stiffness and precision. It is clear that this problem is caused by the manufacturing clearances in the off-the-shelf universal joints used. To overcome this problem, while still using lower-cost off-the-shelf components, other type of joints which has the same motion properties as universal joints but do not suffer from the same backlash problem was investigated as replacements.

The mechanical structure to replace the link with its pair of universal joints is shown in Fig. 9. It is composed of four ball joints connected in a way to form a parallelogram.

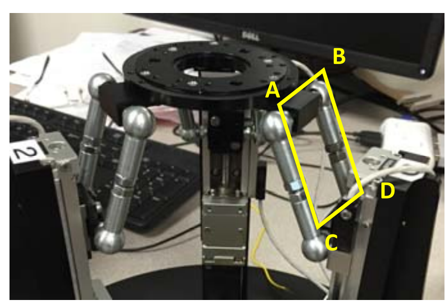

Figure 9. Improved parallel mechanism with ball joints.

According to the property of an ideal parallelogram, the opposite sides of the parallelogram will always be parallel. Therefore, the side *AB* will always be parallel to the side *CD* in Fig. 9. Since the side *CD* is mounted parallel and fixed to the base platform, the side *AB* will also always be parallel to the base platform. As there are three limbs in the TPM mechanism, there are three parallelogram with three sides *AB* attached to the top platform.

These three parallelogram limbs are attached to the top platform such that the three sides AB all lie in a plane and the top platform is parallel to this plane. Since all the three sides AB are parallel to the base platform, the plane formed by them will be parallel to the base platform. Therefore, the top platform will also always be parallel to the base platform. With the top platform constrained to be parallel to the base platform, and the base platform is fixed and immobile, the motion of the top platform will be constrained to be translational only.

If there is free play or backlash in the ball joints at A, B, C, or D in Fig. 9, then the parallelogram formed will not be an ideal parallelogram. In this case, the sides AB may become non-parallel to the side CD. The amount of non-parallelism depends on the amount of free play in the ball joints and the length of the sides AB and CD, the longer the sides are, the smaller the degree of non-parallelism.

For the typical applications they are intended for, good quality ball joints have almost no free play or backlash. The length of the sides AB and CD of the parallelogram are also much longer than the length of the cross component in the universal joints. As such, the use of ball joints with a parallelogram structure for the three limbs of the TPM mechanism effectively eliminated the free play and backlash problem. The resulting second prototype is rigid and has high precision in positioning. With the actuator fixed in their positions, there is no measurable backlash in the top platform. The backlash found in the first prototype had been effectively eliminated and this second prototype will be suitable as the mini in a macro-mini manipulator to be used for finishing and deburring applications for which both position and force/position control are required. Unlike a serial-link robot, the parallel structure of this robotic device gives it the high rigidity and thus the capability of exerting large forces on the workpiece in force-controlled polishing applications

V. Conclusions

A parallel mechanism, based on the structure of the Delta robot, was designed and implemented to serve as a mini manipulator, acting as an end-effector, in a macro-mini manipulator configuration for polishing and deburring applications.

Kinematic models of the mechanism were first obtained and applied to fulfil the given criteria. Solid models were created to simulate and analyze the resulting motions and workspace of the mechanism which was design. Unexpected and unacceptable motions of the top platform in the mechanism were observed during the simulation experiments. The kinematic models failed to explain the motion since the assumption of pure translational motion of the top platform did not hold. It is likely that the non-parallel motions of the top platform in the mechanism was due to it passing through a singular position at which it gained extra degrees of freedom.

With the motion of the actuators in the mechanism constrained such that no singular positions lie within the workspace, the problem of non-parallel motions can be resolved. Further research will be done to determine the exact cause of the rotational motions of the 3-PUU parallel mechanism during simulation.

Unacceptable free play and backlash was exhibited by the first prototype. This was not evident in the simulation experiments which are based on perfectly manufactured components. Investigations showed that this problem was due to inaccuracies in the dimensions of the components used. The main cause was the free play in the off-the-shelf universal joints used for the first prototype. To overcome this problem the universal joints were replaced by off-the-shelf ball joints forming a parallelogram structure for the three limbs of the mechanism. The kinematic model of the mechanism remains the same but the free play problem was effectively eliminated and the second prototype exhibits high stiffness and positioning accuracy.

Lessons were learned from unexpected outcomes and failures during the simulation experiments and in implementation. Properly designed simulation experiments may produce results not predicted by theoretical studies as these studies are normally based on certain simplifications and assumptions, which cannot be completely replicated in simulation experiments.

Furthermore, straightforward simulation experiments which are based on perfect physical properties of the component parts may not show up possible inadequacies in the design. These inadequacies may show up only in the prototypes built due to unavoidable imperfections in the physical components making up the whole system.

Acknowledgment

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Intelligence Level Performance Standards Research for Autonomous Vehicles

Roger B. Bostelman, Tsai H. Hong, and Elena Messina

Abstract— **United States and European safety standards have evolved to protect workers near Automatic Guided Vehicles (AGV's). However, performance standards for AGV's and mobile robots have only recently begun development. Lessons can be learned from research and standards efforts for mobile robots applied to emergency response and military applications. Research challenges, tests and evaluations, and programs to develop higher intelligence levels for vehicles can also used to guide industrial AGV developments towards more adaptable and intelligent systems. These other efforts also provide useful standards development criteria for AGV performance test methods. Current standards areas being considered for AGVs are for docking, navigation, obstacle avoidance, and the ground truth systems that measure performance. This paper provides a look to the future with standards developments in both the performance of vehicles and the dynamic perception systems that measure intelligent vehicle performance**.

I. Introduction

Automatic Guided Vehicles (AGV's) have typically been used for industrial material handling since the 1950's. Since then, U.S. [1] and European [2] AGV safety standards have evolved to protect nearby workers. These standards have minimal test methods to describe how manufacturers and users are to perform AGV safety measurements, resulting in potential measurement differences across the industry. For example, American National Standards Institute/Industrial Truck Safety Development Foundation (ANSI/ITSDF) B56.5:2012 provides new language to generically handle a situation when an object suddenly appears within the AGV stop region. The stop region is the area surrounding the AGV in which the non-contact safety sensor detects obstacles and stops the vehicle. The manufacturer must now prove that when the AGV detects an object closer than its stopping distance, although collision with the object is perhaps imminent, the AGV demonstrates a reduction in kinetic energy. However, there is no description of how manufacturers measure this situation, resulting in different measurement results across manufacturers. One test method was researched to handle this situation and is described in [3].

Recently AGV and mobile robot performance standards developments have begun to limit measurement method differences. Initial developments began with a review of other research and standards efforts for mobile robots as applied to emergency response and military applications [4]. This reference also discusses research challenges, test and evaluations, and intelligent systems development programs that can support advancement of industrial AGVs towards attaining greater levels of intelligence. These other efforts also provide useful standards development criteria for AGV performance test methods. Experiences and results in advanced mobility and intelligence for robotics will be essential for AGV manufacturers and users to fully understand capabilities and specific applications of their autonomous vehicle systems.

Performance test methods for docking, navigation, (see Figure 1) [5], and terminology standard work items have been initiated under the new ASTM Committee F45 on Driverless Automatic Guided Industrial Vehicles performance standard [6]. Standards for autonomous industrial vehicle obstacle avoidance and protection, based on past research [7], communication and integration, and environmental impacts are also being considered.

This paper will specifically discuss measurement of: vehicle navigation (e.g., commanded vs. actual AGV path-following deviation), vehicle docking (e.g., AGV stop point positioning vs. known facility points), and obstacle detection and avoidance of standard test pieces (e.g., comparison of real-time AGV path-planning and new path following vs. commanded path) towards smart manufacturing applications, such as assembly and unstructured environment navigation. Additionally, this paper will discuss a new ASTM Committee on 3D Imaging Systems E57.02 [8] standard work item for six degree-of-freedom (DOF) optical measurement of dynamic systems (see Figure 2), which advances the existing static 6 DOF standard [9]. The new standard is expected to be a critical component of performance measurement for current and future robotic systems that rely on advanced perception systems.

II. Performance Standards Thrusts

AGV navigation, docking, and obstacle detection and avoidance tests were conducted in support of future performance standard test methods and are described in this section. In some instances, typical industry practices were evaluated as well as the improved AGV performance tests.

R. V. Bostelman is with the National Institute of Standards and Technology, Gaithersburg, MD 20899, USA and with the IEM, Le2i, Université de Bourgogne, BP 47870, 21078 Dijon, France (phone: 301-975-3426; fax: 301-990-9688; e-mail: roger.bostelman@nist.gov).

T. H. Hong, is with the National Institute of Standards and Technology, Gaithersburg, MD 20899, USA (phone: 301-975-3444; fax: 301-990-9688; e-mail: tsai.hong@nist.gov).

E. Messina is with the National Institute of Standards and Technology, Gaithersburg, MD 20899, USA (phone: 301-975-3510; fax: 301-990-9688; e-mail: elena.messina@nist.gov).

A. Vehicle Navigation

The most basic functions of mobile robots and AGV's are navigation to and docking with equipment in the workspace. However, the description of how well the vehicle navigates (i.e., commanded vs. actual AGV path-following deviation) has certain ambiguities. For example, navigation implies that the vehicle measures its current position, plans a route to another location, and moves from the current location to planned location upon command. Most vehicle manufacturers don't provide specifications for how uncertain the navigation performance is (i.e., the error bounds on position or velocity), other than perhaps radius of vehicle turns, maximum velocity, and maximum acceleration. The vehicle velocity sets limits on the allowable turn radius for particular vehicles. Some controllers [10], if not all, will not allow high velocities on relatively small radii to prevent unsafe vehicle conditions. These limitations are not typically specified by AGV manufactures, causing AGV users difficulty in planning how many vehicles they may require for moving their products within the facility to maintain a desired throughput.

Industrial vehicles may eventually become uncalibrated through regular use. An uncalibrated vehicle does not follow a commanded path or stop/dock at a commanded point with minimal relative uncertainty (standard deviation of measured vs. ground truth) as does a calibrated vehicle. To correct this, vehicle manufacturers have calibration procedures for their vehicles, although these procedures can be tedious, time-consuming, and may not be appropriate for all vehicles. For example, calibration of Ackerman steered vs. 'crab' steered (sometimes called quad) vehicles have different calibration procedures. It is not always clear what will happen when a vehicle is uncalibrated nor when the vehicle becomes uncalibrated. The effects of calibration on vehicle control and uncertainty are typically not specified either. There is also typically no specification describing how far from the commanded path a vehicle navigates. This may be important to users who have tight tolerance AGV paths (e.g., paths between infrastructure) that must be followed. A test can be developed to uncover the effects of uncalibrated vs. calibrated vehicle navigation performance when commanded to move along a path, as shown as a dashed line in the example in Figure 1. Should objects be near the vehicle path, such as walls or obstacles, depicted in Figure 1 as bordering lines along the path, the vehicle may stop, slow, or worse, collide with the boundary object. A user would then be required to provide additional, perhaps unnecessary space for one manufacturers' vehicle and not for another. How the vehicle handles (slow, stop, etc.) the event is also ambiguous. For example, some, but not all vehicles are equipped with obstacle detection based on non-contacting sensors that provide detection beyond the physical vehicle footprint.

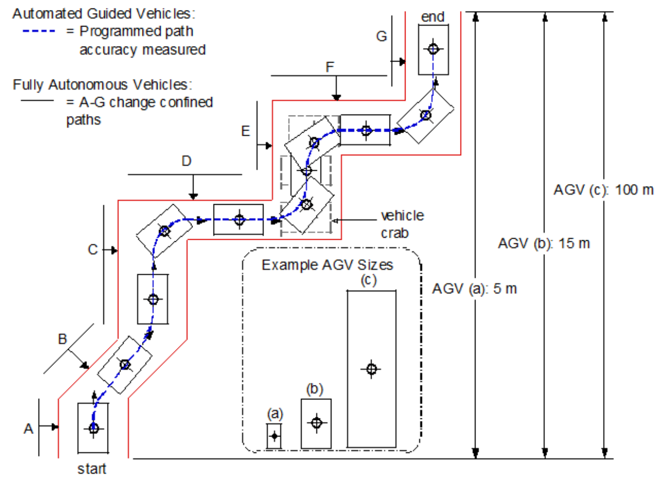


Figure 1. Example reconfigurable apparatus for navigation tests for various AGV sizes.

To address AGV navigation uncertainty, with an eye towards a potential test method for all automatic industrial vehicles, tests were executed, both with an AGV prior to and after being calibrated. The uncalibrated AGV test is similar to typical industry methods since not all AGVs can be frequently calibrated. An uncalibrated AGV was moved along a straight line path between two commanded points in an open area and spaced approximately 5 m apart [5]. Figure 2 shows the results amplified in the X direction 100 times to exaggerate vehicle performance. In the figure, the blue line is the commanded path between points 1 and 2. The green dots to the right and left of the line are uncalibrated AGV controller-traced position data moving forward and reverse, respectively, between the points. The red dots are ground truth of the navigating AGV between points using an optical tracking system. This experiment demonstrated one AGV navigation performance measurement method using a precision (0.2 mm standard deviation) six degree-of-freedom (DOF), optical measurement system as a ground truth comparison to the onboard vehicle tracking system. Path deviation was approximately 20 cm maximum. The AGV was then calibrated using the manufacturer's method.

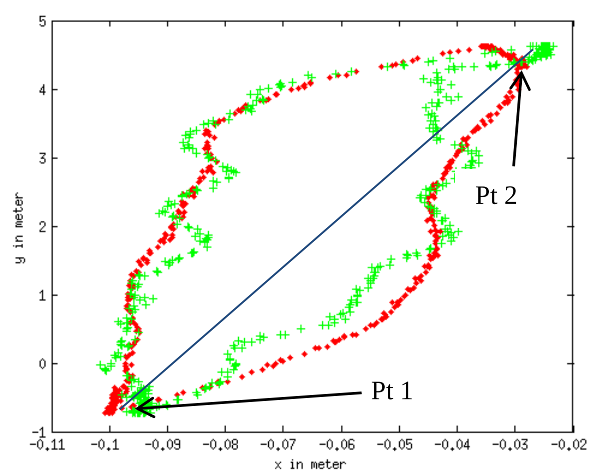


Figure 2. Ground Truth (red) and AGV (green) data of the straight line path tests. Scales for X and Y axes are in meters where the X axis shows only -0.11 to -0.02 range to clearly show the AGV performance as compared to Ground Truth measurement. The blue line represents the commanded path from pt 1 to pt 2 and back.

Another test setup was tried, with an eye towards a relatively less expensive test method that will allow all AGV systems to be measured, ideally, with an independent measurement method that doesn't use AGV controller tracking, yet captures the full AGV configuration (i.e., including safety sensing). The AGV was commanded to drive back and forth between temporary barriers, along a straight line defined by commanded points spaced approximately 10 m apart. The goal of the experiment was to measure the AGV deviation from the commanded path. A critical AGV navigation performance area is also deviation from the commanded path after turns so a 90° turn was added to the end of the straight path beyond the barriers to measure the vehicle navigation uncertainty when moving from/to a straight path to/from a turn. Figure 3 shows the test setup and Figure 4 shows (a) a B56.5 test piece being used to define the safety laser stop field edges, (b) the barriers and lines to which barriers are moved between trials, and (c) the AGV emergency-stopped upon detection of the barriers. The safety laser, stop field edges were marked on the floor, as a ground truth, zero-tolerance spacing that the vehicle can navigate, when the vehicle was at position 1 and again at position 3, shown in Figure 3, for both left and right vehicle sides. The barrier position lines were measured from the edge line using a ruler and marked at 2 cm increments from the edge up to 10 cm away from the edge line. Smaller spacing between lines (e.g., 1 cm) could also be used for finer uncertainty measurement. For each test trial, the barriers were moved towards the AGV to the next line beginning at 10 cm for trial 1, 8 cm for trial 2, and so forth until the navigating vehicle detected a barrier, and emergency-stopped the AGV, thus completing the test run.

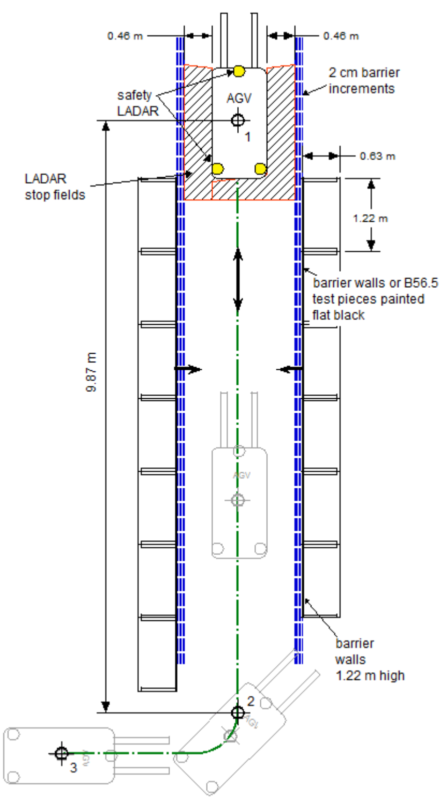


Figure 3. AGV navigation test setup.

A series of eight trials were completed with nearly all trials including three or more runs each to demonstrate the navigation test method concept. Ten or more runs are ideal for statistical analysis. The optical measurement system mentioned earlier was used as an experimental ground truth (GT) to measure the barrier and vehicle position during experiments to further understand the test method and vehicle performance. The barriers and AGV were marked with spherical reflectors (visible in Figure 4 (a, b, and c) detectable from the GT system. Figure 5 presents GT data plotted for navigation tests showing ground truth data of: (a) test 8 vehicle path and emergency stopped vehicle (red circle) when a wall was detected, (b) test 1 path, and (c) test 1 path data from (b) zoomed in to show data points of three runs.

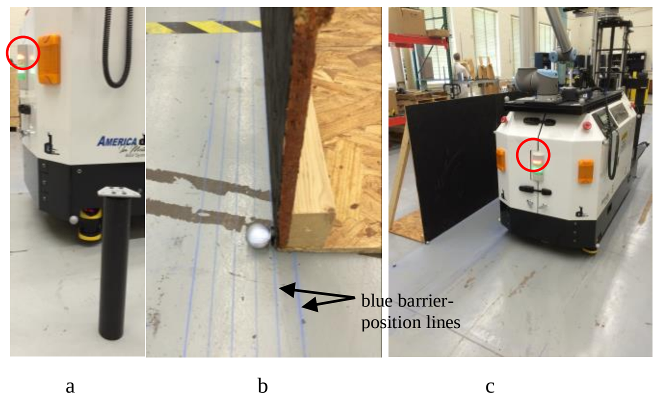


Figure 4. (a) B56.5 test piece (black cylinder) used to define safety laser edge (note red emergency stop light (within the red circles) is on), (b) barrier (black) painted wood panel, blue lines spaced at 2 cm, and spherical reflector from ground truth system, (c) AGV emergency stopped, as noted by the red light, upon detection of barriers during a test.

Experimental results from the barriers demonstrated a path uncertainty of between 6 cm and 8 cm maximum when the vehicle detected the boundaries at nearly the center of the straight line path and when moving at either 0.25 m/s or 0.50 m/s. The navigation test method using barriers is simple and cost-effective for manufacturers and users to employ, as compared to the higher accuracy, but more expensive ground truth visual tracking system used for test method development. A simple straight line with one turn was tested. However, more complex test configurations, such as shown in Figure 1, could be set up using B56.5 test pieces instead of larger, physical barriers as were used in this research.

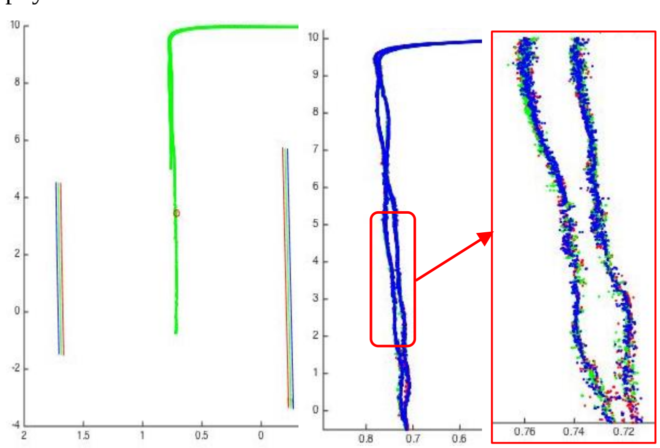


Figure 5. Example graphical results of navigation tests showing ground truth data of: (a) test 8 vehicle path and emergency stopped vehicle (red circle)

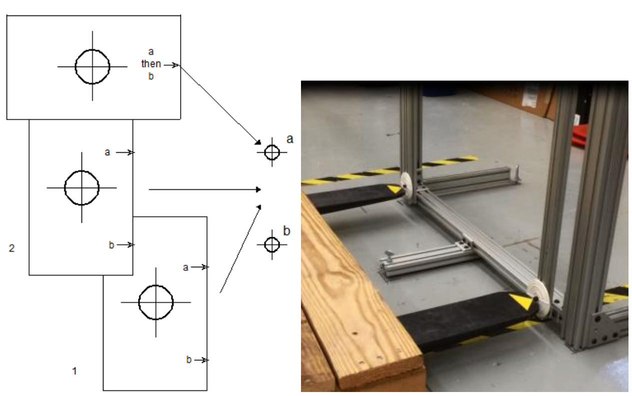
when a wall was detected, (b) test 1 path, and (c) test 1 path data from (b) zoomed in to show (red, green and blue) data points from three runs.

A working document that addresses quantifying vehicle navigation uncertainty is being developed as an initial step towards a performance standard for ASTM F45.02 subcommittee on Docking and Navigation. Based on consensus of the task group developing this standard, as was tested at NIST, the simple path-bounding test method using temporary reconfigurable barriers made from readily-available, off-the-shelf materials is being proposed.

B. *Vehicle Docking*

Vehicle docking is another common application of mobile robots and AGVs. Unit load (tray, pallet, or cabinet carrying), tugger (cart pulling), and fork/clamp (pallet or box load/unloading) are typical industrial style vehicles that require different docking uncertainties. For example, a unit load vehicle that places/retrieves platters during wafer manufacturing would no doubt require less uncertainty than a fork style vehicle that places/retrieves pallets. As robotics advances, current and potential users are requesting mobile manipulators to perform tasks such as unloading trucks. Eventually, it is expected that mobile manipulators will be used for smart manufacturing assembly applications [11, 12].

Similar to navigation, there are no performance measurement test methods that define how manufacturers and users characterize their vehicle's docking capabilities. Figure 6 (a) shows an example method for docking for any style vehicle. A vehicle approaches and makes contact with 'a' and/or 'b' docking points dependent upon the vehicle type. Relative displacement from each of the points would be measured to determine vehicle docking uncertainty. A fork-type AGV is shown docked with a test apparatus in Figure 6 (b). The fork tips are marked with yellow points.



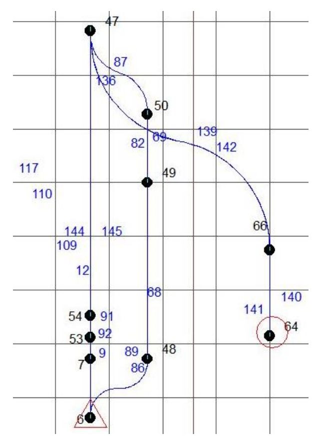
(a) (b)

Figure 6. (a) Example docking test method using various AGVs (e.g., 1 and 2 for AGV unit load tray table docking, 3 for fork and tugger AGV docking). "a" and "b" are fixed points in space (e.g., contact or non-contact sensor locations in space). Approach vectors and sensor point spacing and locations are variable. (b) Fork-type AGV docking with a docking apparatus.

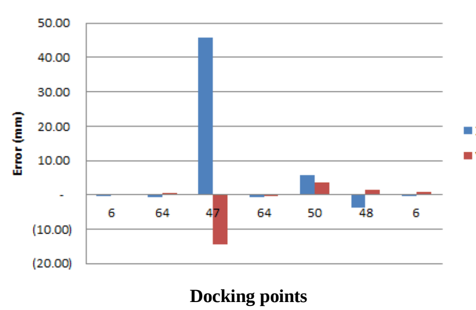
Two experiments were simultaneously performed: AGV docking relative to known facility locations and GT system use for measuring AGV docking. Two different GT measurement systems were used to measure AGV performance: a laser tracking GT with an uncertainty of approximately 10 µm [13] and an optical tracking system with uncertainty of 0.2 mm in position uncertainty and 0.13° in angle uncertainty as measured at NIST. The laser tracker tracks position of a single point, whereas the visual tracking system can track multiple point markers and can computer orientation from them. Both GT systems can measure relatively high-precision displacement between two points, as compared to an AGV docking.

An experiment using an uncalibrated AGV that was programmed to stop at various points yielded an uncertainty range of approximately 1 mm to 50 mm. Figure 7 (a) shows the vehicle paths and Figure 7 (b) shows average errors for five runs at stop or dock points. The vehicle position was measured using a laser tracking GT system which provided high-precision measurement of AGV stop points. [13] However, in several experiments, laser tracker positioning was critical as the laser beam was continuously interrupted by onboard AGV hardware. This prompted a switch to using an optical tracking system for GT measurements.

A 6 DoF optical tracking GT system was used instead to measure AGV docking. Docking was measured again after the AGV was calibrated using the manufacturer's procedures. The AGV approached similar dock locations and after AGV calibration, provided consistent 5 mm uncertainty. Standards development for optical tracking systems is also underway and is discussed in section 2 D, 6 DOF Optical Measurement of Dynamic Systems.



(a)



(b)

Figure7. (a) Commanded paths and stop points and (b) stop point errors of a single AGV point for each location in (a) averaged over 5 runs.

Additional AGV equipment docking experiments were also performed using a mobile manipulator and a reconfigurable mobile manipulator artifact (RMMA) developed at NIST (see Figure 8). [14] The mobile manipulator, with uncalibrated AGV, repeatedly moved next to the artifact from a starting point. Although uncalibrated, the

AGV provided relatively low repeatability uncertainty (e.g., +/-5 mm) although more than 10 mm from the commanded docking points. This manipulator could reach the commanded points on the RMMA even with 10 mm uncertainty in AGV position. The mobile manipulator corrected for the position uncertainty after being taught the actual RMMA locations. At the RMMA, the manipulator, wielding a laser retroreflector, was commanded to move in a spiral pattern to detect 6 mm diameter reflectors. The reflectors provide non-contact alignment detection of the tool point position and orientation. The experiment provided results demonstrating that this relatively inexpensive ground truth measurement method was sufficient for measuring docking accuracy. As the reflector based measurement system is inexpensive compared to the optical tracking-based GT, it may prove ideal for use as a precision vehicle/mobile manipulator docking test method that both manufacturers and users can replicate.

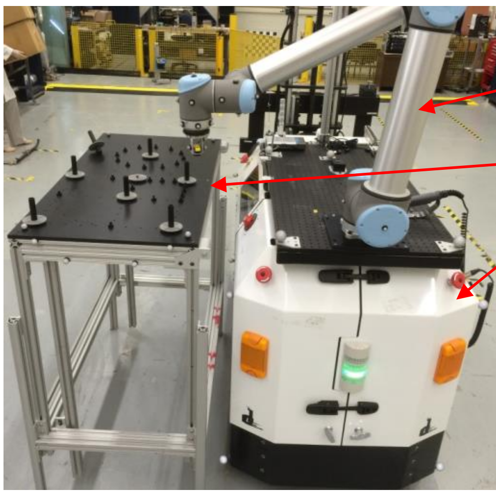


Figure 8. Docking performance measurement of a mobile manipulator with a reconfigurable mobile manipulator artifact (RMMA).

C. *Obstacle Detection and Avoidance*

Obstacle detection and avoidance (ODA) research is well documented in the literature for mobile robots. However, there are few citations for AGVs perhaps due to the relatively closed nature of commercially available AGV controllers and because ODA is not often implemented on AGVs deployed in large manufacturing facilities. In [5], it was discussed that for large facilities, ODA could occur in 'buffer zones' (i.e., zones where AGVs would be allowed to pass other vehicles). For small and medium manufacturing facilities, however, ODA may be necessary due to more limited floor space and less-controlled environments. NIST has developed an algorithm, detailed in [5], and measured the performance of an AGV with added ODA capability. The algorithm is also suitable for navigating an unstructured environment although it is currently limited by the use of facility-mounted (sensors not mounted on the AGV) obstacle detection with obstacle avoidance adapted to an AGV with a controller with limited ability to integrate external algorithms. Figure 9 shows a snapshot of the ODA algorithm planning a path through multiple obstacles.

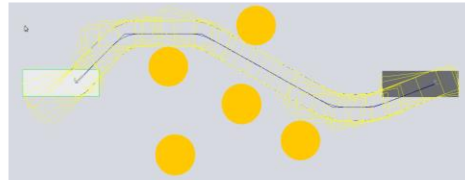


Figure 9. Graphical output of path planner, starting footprint of the AGV is in white, the goal position is a dark grey rectangle. Yellow rectangles show the area swept out as the AGV would travel, blue curve shows the resulting spline, and orange circles represent obstacles.

The navigation performance measurement experiment discussed previously in section II A. Vehicle Navigation can be similarly applied for obstacle detection and avoidance. In fact, the ASTM F45.02 subcommittee navigation and docking task groups have discussed the potentially overlapping nature of the two vehicle capabilities. The ASTM F45.03 Obstacle Detection and Protection subcommittee is currently in the process of considering standards in this area. Questions have been raised regarding standards development as follows:

1. How well does the AGV react to situations? For example:
   - Obstacles appearing in the path
   - Potential obstacles headed towards the path
   - Unstructured (i.e., changing obstacle locations) areas not on the original planned path or that rapidly change
2. How far off the commanded navigation path can an AGV be, and at what speeds, before it violates the path and causes a stop? For example, due to environmental factors such as:
   - Offset-pitched/rolled AGV can't see guidance markers, such as reflectors, magnets, wire, etc.
   - Guidance or boundary-marking tape is worn or broken
   - Terrain causes "bouncing" or moving laser or other navigation sensors
3. How well does the vehicle react when a human is detected and how should the human be represented? For example:
   - By test pieces, mannequins, humans
   - With what coverings? (i.e., what clothes should be worn?)
4. How to interact with manual equipment (e.g., forklifts, machines)
5. How to standardize communication of vehicle intelligence for obstacle detection and avoidance? For example:
   - Contextual autonomy levels [4]
   - Situation awareness (e.g. LASSO) [14]:

Experiments to support ODA performance test method development will be performed based on forthcoming guidance from the ASTM F45 subcommittee. However, a prototype safety test method that has been developed to evaluate a vehicle's response to obstacles in its path and within its stop zone, as noted in the Introduction, can be considered a first step towards full ODA standard test methods. ASTM F45 is meant to dovetail with safety standards such as ANSI/ITSDF B56.5. Therefore, providing an initial test method for detection of obstacles is ideal as a starting point for F45.03. The 'Grid-Video' detection method [3] provides a simple-to-implement test method that measures positional accuracy of the dynamic test piece relative to the vehicle position when the obstacle enters the vehicle path.

D. *6 DOF Optical Measurement of Dynamic Systems*

ASTM's draft Standard for the Performance of Optical Tracking Systems that Measure Static and Dynamic Six Degrees of Freedom (6DOF) Pose (see Figure 10) is the next step beyond the static case covered by ASTM E2919-14 [8]. Optical tracking is being used for robot and autonomous vehicle GT measurement, as discussed in this paper. Optical tracking measurement systems [15] are used in a wide range of fields, including video gaming, filming, neuroscience, biomechanics, flight/medical/industrial training, simulation, and robotics. ASTM WK49831 is a working document that is considering both static and dynamic measurements of systems under test. The scope of the draft standard test method is to provide metrics and procedures to determine the performance of a rigid object tracking system in measuring the dynamic pose (position and orientation) of an object. Optical measurement systems may use the test method to establish the performance for their 6 DOF rigid body tracking pose measurement systems. The test method will also provide a uniform way to report the statistical errors and the pose measurement capability of the system, making it possible to compare the performance of different systems. So all the measurements can be traced to the standard.

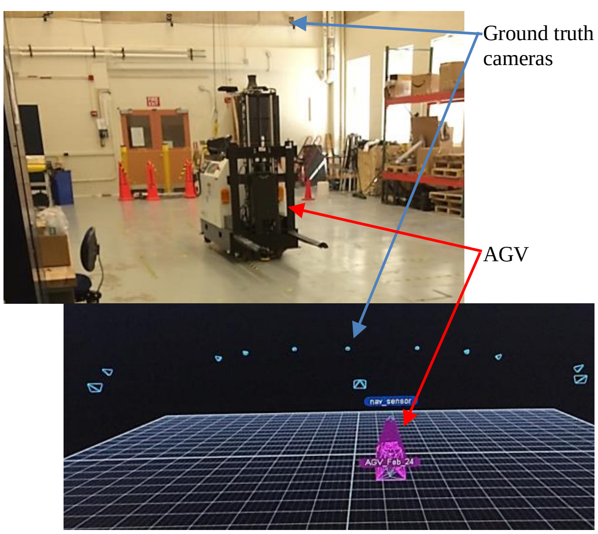


Figure 10. (top) autonomous vehicle test lab and (bottom) screenshot of the perception ground truth system space showing cameras and vehicle rigid body.

In the initial test procedure, measurements with uncertainties were computed using an artifact – namely a metrology bar as shown in Figure 9 (a). Current optical tracking systems utilize a three-marker metrology bar with all markers in a line which does not provide 6 DOF system performance measurement. A metrology bar made of carbon fiber with length 620 mm and with five reflective markers attached on each end was used as the 6 DOF artifact. A carbon fiber bar is used since it limits the effects of thermal expansion. The metrology bar markers on each end form a constant relative 6 DOF pose between the two ends. A shorter bar length should be used for smaller space measurements to maximize metrology bar movement during dynamic measurements.

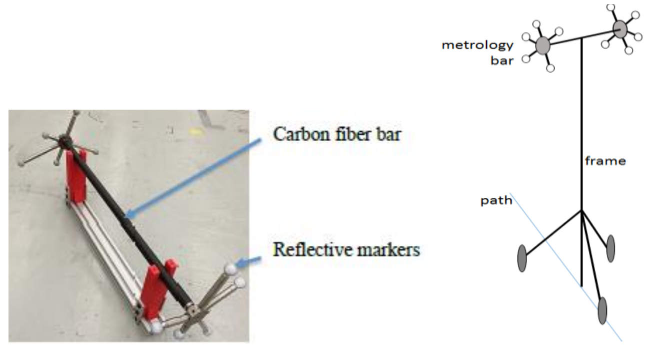


Figure 9. (a) Proposed metrology bar, (b) Example frame used to move the metrology bar.

Most optical tracking systems have at least a 30 Hz data collection rate. Therefore, a minimum of 5 min of data needs to be collected. The workspace is uniformly divided by the artifact length. The artifact is moved using at least the minimum and maximum motion capture velocity specified for the system.

The static test procedure for measuring the performance of the optical tracking system is to divide the test space into a grid and place the artifact at intersections of the grid and at various orientations. The dynamic test procedure also divides the test space into a grid where the metrology bar is moved in a raster scan pattern forward-to-back and left-to-right throughout the space.

The metrology bar maintains a constant separation and orientation of the two marker clusters along all the paths and can be rigidly attached to and moved using a wheeled frame as illustrated in Figure 9 (b) that is pushed/pulled by a human, a mobile robot, or other mover to closely follow the path.

The metrology bar is moved at the maximum specified velocity of the optical tracking. Pose error measurement and reporting methods are also described in the ASTM WK49831 [8] working document.

III. CONCLUSION

The AGV standards development process has been limited for many years to considering only safety standards. Starting in late 2014, ASTM F45 Driverless Automatic Guided Industrial Vehicles performance standards are being developed to include navigation, docking, terminology and several other key areas for AGV's, mobile robots, and mobile manipulators. As discussed in this paper, standard test methods for measuring vehicle performance are being developed so that manufacturers and users of these systems can easily replicate the measurements in their own facilities and at minimal cost and effort. More AGV and mobile robot systems, instead of just the one AGV used in these experiments, would ideally validate the generic test method proposed.

A comparison of GT measurement systems was also made to support the test method development. It was determined that for dynamic AGV measurement, an optical tracking system provided a suitable ground truth measurement. At the same time, a standard for these dynamic measurement systems is also being developed. The standard will allow vehicle and robot performance standards developers to use the systems as ground truth with known measurement uncertainty. Optical tracking systems users and manufacturers can replicate the same test methods with similar tracking systems and use the results to compare their performance at dynamic tracking tasks.

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Gualzru's path to the Advertisement World

F. Fernández, M. Martínez
Planning and Learning Group
University Carlos III Madrid
Email: {ffernand}@inf.uc3m.es

I. García-Varea, J. Martínez-Gómez
SIMD
University Castilla-La Mancha
Email: {ismael.garcia,jesus.martinez}@uclm.es

J.M. Pérez-Lorenzo, R. Viciana
M2P
University of Jaén
Email: {jmperez, rviciana}@ujaen.es

P. Bustos, L.J. Manso, L. Calderita,
M. Gutiérrez, P. Núñez
RoboLab
University of Extremadura
Email: {pbustos, lmanso, lvcalderita, marcog, pnuntru}@unex.es

A. Bandera, A. Romero-Garcés,
J.P. Bandera, R. Marfil
Ingeniería de Sistemas Integrados
University of Málaga
Email: {ajbandera, argarces, jpbandera, rebeca}@uma.es

***Abstract*—This paper describes the genesis of Gualzru, a robot commissioned by a large Spanish technological company to provide advertisement services in open public spaces. Gualzru has to stand by at an interactive panel observing the people passing by and, at some point, select a promising candidate and approach her to initiate a conversation. After a small verbal interaction, the robot is supposed to convince the passerby to walk back to the panel, leaving the rest of the selling task to an interactive software embedded in it. The whole design and building process took less than three years of team composed of five groups at different geographical locations. We describe here the lessons learned during this period of time, from different points of view including the hardware, software, architectural decisions and team collaboration issues.**

I. Introduction

Gualzru is a social robot built as an advertisement tool for a consortium of technological and digital media companies within the ADAPTA[1] project. The core of this project is an interactive panel able to provide personalized advertisement according to the preferences of the user. To achieve this goal, the consortium includes advertising companies, media asset management, software developers, technological consultants and software infrastructure providers, coordinated by the Software Labs group from the Spanish Indra company. The idea of using a robot as a more personal way of bringing people's attention was suggested in order to endow the panel with the ability to recognize the emotional state of the user and to classify her according to the estimated age and gender. After agreeing on creating a new social robot, it was decided that Gualzru, would team up with the interactive panel and boost the advertisement potential of the platform. The project started in May 2012 and this paper describes our experiences, successes and failures, during the three-year process.

II. The team

From the early analysis of the problem we knew that the project needed the expertise from different research groups. So, once a solid group of complementary researchers was agreed, we accepted to join the project's consortium. Our first 'robotic' consortium was composed by the Universities of Málaga, Extremadura and Carlos III of Madrid. From 2010, the first two groups were working together on the definition of a software framework for robotics, which could be used for the project. The University of Extremadura would also build the platform and would be the responsible of endowing the robot with the abilities for autonomous navigation and facial emotion detection. The University of Málaga would address the rest of vision-based problems (e.g. use facial descriptors to estimate the gender or age) and help with the navigation modules. Finally, the University of Carlos III of Madrid would be in charge of the high-level planning and learning modules. Everyone agreed in using this project as a test for the initial proposal from the University of Extremadura: to organize the whole software architecture around a centralized internal model of the outer world. Such representation is accessed by all software components to keep them informed about the current world state. They can also update it as the result of processing the data from the sensors. The ADAPTA project will provide a controlled but realistic scenario for testing the idea.

One major requirement of the proposal that the robot initially lacked was the ability to dialogue with people. To solve this problem the SIMD group from the University of Castilla-La Mancha, summing a large expertise on automatic speech recognition and natural language processing, joined the Consortium. Furthermore, the human-robot interaction ability was strengthen with the incorporation of the researchers from the University of Jaén. Six researchers from all groups were contracted during different periods of time to work on the project, however a larger group of researchers was always involved on the project.

A. Team coordination and sharing of resources

The coordination of this large group was supported by the use of collaborative tools. However, we soon understood that the only way to make a steady progress in the development of a large and complex project like ADAPTA, was by sharing a common code base and by scheduling periodic hackathons

[1] See Acknowledgments section at the end.

Fig. 1. Gualzru the robot

in which the members of all the teams could seat together for a week and fight a specific, common battle. This strategy naturally led to the division of the project in well defined milestones, consisting on system features to be integrated and tested during the one-week period. Coordination was therefore subtended on:

- A unique robotic prototype, available from month zero in a robotics simulator.
- A common programming framework, RoboComp [17], used in several previous projects. All the software developed for the project had to qualify as a RoboComp component, meeting the established quality standards, and had to be uploaded to a common git repository.
- A common cognitive architecture, RoboCog, available for all researchers and where individual modules could be inserted and tested minimizing the knowledge required about the rest of the architecture
- The organization of several intensive working weeks -hackathons- coinciding with the project milestones. These meetings were intense and dedicated to integrate and debug specific target functionalities.

To maintain the global view of the project and of the specific requirements, all the members should meet for each milestone and have always access to an open document storing this information. The document was edited online by all researchers and also served as a battlefield to discuss technical issues. We did not always coincide about how to do things but we agreed that the digital arena was the right place to fight.

III. Gualzru

Gualzru, a phonetic transcription of the English phrasal verb "walk through" pronounced by a native speaker of Extremadura, is a 1.60m. tall robot with an external cover built of resin and fiber glass, and a differential base with two powered wheels and two casters. It includes gel lead batteries that provide an autonomy of three hours and all the necessary power electronics, recharging and power supplies for the sensors and processors. The complete fabrication of the robot was custom made by the groups of the consortium.

Table I shows the complex handcrafting process of Gualzru's external cover. This step was one of the most exasperating and time-consuming in the overall development of the project. It was a relatively new process for us with many steps that were out of our direct control. Going in Table I from top to botton and from left to right, we can rapidly summarize the manufacturing steps:

1) Gualzru's initial 3D design. To come up with a nice robot image we set up a public design contest among all Spanish universities and people and companies in the design business. One person from Cádiz, Spain, was selected among more than 30 proposals with a poll among a selected resolution committee.
2) The 3D drawings were sent to a company specialized in manufacturing expanded polystyrene molds using industrial CNCs. We learned that the choice of prices and qualities here are apparently important, since the final quality of the surface of the cover and the number of hours spent by the sculptor in fixing the small imperfections generated in the machining process were closely related. It is important to assure the final quality level in this early stage.
3) An external coating over the mold is necessary to facilitate the unmolding process. The mold is split in two halves.
4) A thick silicone layer is manually applied on the mold with additives to avoid sagging. This layer is called *negative*.
5) On top of the silicone a resin with fiber glass layer is applied to create a rigid external cover called *mother*.
6) Both layers are unmolded.
7) The silicone mold after being separated.
8) A *positive* mold is finally built by applying resin and fiber glass inside the *negative*. After drying, the cover is unmolded from the silicone and both parts are glued together. A final polish work is done to obtain a nice texture.
9) A solid and reliable differential base is built as the mechanical core of the robot.
10) The cover is fit on the base. Additional holes and slits have to be carved to allow for laser, camera, fastening, etc.
11) Sensors are incorporated to the robot. The tactile screen is placed after a final coating is ordered to a car painting workshop.
12) Gualzru at the University of Málaga in a public event with the University's Provost.

As a summary of the experience it is evident that the process is slow, expensive in working hours and almost impossible to rectify if a new idea comes by. The whole process took us many more months than expected and we had to use a replacement Nomad 200 robot while the robot was being built. In summary, it is a valid solution to the cover problem but with the arrival of 3D printing technology, all chances are that future robot covers will be divided in pieces small enough to be printed in a modern 3D printer, and then assembled together. There are also new small companies starting to offer these kind of services.

TABLE I

A SERIES OF SNAPSHOTS OF THE BUILDING PROCESS OF GUALZRU. SEE TEXT FOR DETAILS ON EACH STEP AND THE CONCLUSIONS OBTAINED AFTER IT WAS FINISHED.

IV. ROBOCOMP

As commented in section II-A, one of the few things that were already clear when the project started, was the need of a common code base.

A big part of the group had been already working in previous projects together and sometimes with other partners. From these works we learned that one of the main causes that prevented the formation of a cohesive, long lasting group with a common goal was the fact that each one was coding their own programs on different frameworks or without one at all. There are many robotics labs around, still unable to organize and create a coherent code base that grows from the accumulated work of dozens of researchers. After some tough negotiations involving the different frameworks that the groups were using or planning to use, we agreed to use RoboComp. We believe there are several reasons that, in the hindsight, justify this decision:

- We keep the control of the core and thus, we decide when to change and when to hold. It looks like a contradiction but when some complex open source software is very soon used by thousands of people, its evolution freezes or slows down almost immediately. The reason is that the core decisions made at the very beginning cannot be easily changed without generating compatibility problems and versions nightmares. As an example you can look at the widely expanded Microsoft's operating system (Windows) and the relatively slow addition of new features with each release (mainly nothing on the core changes). This does not mean that good software cannot be used by many people, but that complex software that deals with new, changing, not very well defined sort of things, takes its time to settle down.
- RoboComp's component model has been evolving since its beginning and has the necessary complexity for our needs. Not more.
- The current communications middleware, Ice by ZeroC [14], is extremely robust. No complaints and a big thank you to an excellent open source project.
- New middlewares could appear in the future with some game-braking features. In that case, if you control the framework you can define a reduced set of communication primitives, like the ones proposed by Schlegel in his PhD thesis [1] and a set of data types, and write some interface code that makes you framework middleware independent.
- A code generator is mandatory so the generic part of the components is always the same, compiles without errors and keeps the required quality levels. Code re-generation might be trickier but there are several techniques. RoboComp splits the working part of the component in two using inheritance. The inherited part is always generated and the part that inherits is generated only the first time. A lesson learned here is that it is easier if all tools and technology in the framework use the same development language and environment. Better if it is the one that most of the users are familiar with. Otherwise the no common specific tool becomes a bottle-neck that might delay and affect other parts of the framework.

  Our initial code generator was created with the Eclipse ecosystem using the existing tools it provides for DSL designs. This tool turned out not to be easily adjustable by developers (since they mostly develop C++ and Python) and a heavy environment that would not exactly match the team needs. Therefore, we ended up rewriting a lighter code generator in Python using *pyparse* and *COG* so everybody could collaborate in the natural evolution of the tool. Now, RoboComp's code generator generates also Python components, that are becoming more a more popular due to their simplicity.

- We have developed all the tools we needed, although there are always tools that we would like to have but we have not had time to code them. RCIS deserves a special mention, RoboComp's simulator, that it has been there almost since the beginning of the framework. By the time RoboComp started the only existing open source simulator was Gazebo and it was in its early versions. If you are building a robotics framework and have already decided on the communications middleware, the chances are that you want a simulator that *speaks* the same language as the components of the framework. Only doing so, the simulator would behave like a component or several components with all the advantages that come with that. Therefore we wrote RCIS using Open Scene Graph [20] and an initial scene specification language that we named InnerModel. Later on, we discovered with great joy that having our own simulator would immediately provide us with an *emulator*. That is, a simulator that could be run inside the architecture computing in super real-time future courses of action and predictions. That is now part of our new architecture CORTEX, which is still in development.

V. RoboCog

Initially, we addressed the ADAPTA project from a very specific point-of-view. That is, giving the use case, we translated it to a finite state machine and assigned tasks to software components or groups of them that we call agents. The idea of using a finite state machine to manage the whole use case was soon unbearable. The number of states and transitions grew with every bit of reality added to scenario. Even modern hierarchical and concurrent formalizations of state-machines [8] and ready to go implementations such as the Qt StateMachine Framework [9] did not offer enough flexibility and maintainability to risk a project with many potential implications for our future.

We thus decided to take the hard way to a fully fledged symbolic planning system, in charge of the automatic generation of those huge state machines. The Planning and Learning Group at the University Carlos III of Madrid had a very long trajectory in these disciplines and was the perfect match to provide the needed technology. The use case was translated into a PDDL domain specification [18] and several planning algorithms were tested for that domain. A separated interface was clearly defined between high and low level domains. High-level being the domain of logic attributes and predicates, and low-level the domain of behavior agents that receive parametrized calls to act and provide metric values for relevant variables of the world state. The interface layer translates between high and low level, so both worlds are kept communicated. Of course, it is also the main cause of the so called, symbol grounding problem [11].

This now familiar scheme was synthesized by Erann Gat as the *three-layered architectures* [2], probably the most extended approach to build deliberative-reactive agent control systems today. However, when making decisions that directly involve human users, the domain of HRI, these architectures present some limitations. The most important one, from our point of view, is the need of a shared representation among all agents including metric and symbolic information, making each of them more aware of what was going on in the rest of the agents. For example, if a navigation module is driving the robot to a target place, and a person appears somewhere close to the planned path, how does the navigation agent differentiate between and obstacle and the person, so different avoiding (social) behaviors can be elicited? Or how does a conversational module knows that the person the robot is talking to, is not paying attention anymore, and thus a change in the discourse is advisable?

To us, it looks like that the good engineering practice of decoupling the problem in parts of *infinite impedance*, took away a crucial element, *context*. It is sometimes argued that context is somehow coded in the interactions between agents [3] or in the dynamics of coupled differential equations [4]. We decided to take here the more classical path of building an explicit shared representation for the context and face the problems to come.

To start, we already had a representation of the robot and its close environment in the form of a scene-graph, called InnerModel. This simple DSL served to initialize our RoboComp's 3D simulator, RCIS. Therefore, RoboComp's InnerModel was the perfect starting point to develop the idea of a shared representation of the robot, the environment and the people in it. The initial scene graph specification language was gradually extended to include more types of objects. Also a C++ class was written to hold in memory the graph and allow an easy and safe access to all the handy functionalities that this structure provided, such as coordinate transformations, measuring, insertion, modification and removing of nodes, perspective changing, frustum reachability, etc.

A basic scene-graph is essentially a kinematic tree with some add-ons. We had to incorporate all the symbolic information needed by the deliberative elements of the architecture. The requirements were that the perception-action related agents could update a fixed set of symbolic attributes and predicates, and that the selected representation could be efficiently translated to PDDL, so a specialized planning, executing and monitoring framework like PELEA [5] could be used. Our election on how to proceed in that situation was not exactly a mistake but it was certainly close to it. We decided to build a second graph, this time a graph rather than a tree, to hold this symbolic data and leave to a less stressed moment the problem of how to integrate both structures. It was not a mistake in the sense that the solution worked well and the robot managed to complete the use case. It was a mistake in the sense that now, months after the end of the project, we are hurrying to finish the integration of both structures because the separation is already generating many problems.

The current solution we are working on is the embedding of the kinematic tree inside the symbolic graph, and the code necessary to efficiently extract and insert the tree in a format that can be used by the many components that were written before the integration. It is hard to evaluate if the other choice would have permitted us to finish the robot on time, saving the posterior integration step. Software developing time is really hard to estimate, specially when robots are in the loop.

The new graph was named AGM, for Active Grammar-based Model [6], and besides fulfilling both requirements, it was also an experiment on planning with a variable number of symbols. In HRI, the perception component is getting more and more important. When interacting with a human in domestic or service environments, there are references to objects and places that may not be known beforehand. Of course, planning in an open world takes you out of the comfort zone of algorithms, where you know that the program will finish. In open worlds, there is always the possibility of adding a new symbol if the solution does not arrive.

AGM and InnerModel where independent structures and their coordination was managed by ad-hoc procedures, but AGM was finished on time and will maintain a complementary, symbolic representation of the robot and the objects in the scene. For example, a human in front of the robot being detected and represented as a skeleton inside InnerModel, could now be tagged *happy*, *focused* or *woman* in AGM. With AGM we had the missing part of the architecture and all the groups could start to meet in hackatons and reach, one by one, the urgent remaining milestones of the project. In summary, the main purpose of this dual representation was to provide both, a local description that could be updated and used by the different agents for their computations, and a shared context that is propagated among them to carry information that otherwise would remain hidden.

As a result of the graphs occupying their places with the agents, the overall idea of RoboCog started to change and we started to move from the three-tier original model to a non-hierarchical disposition in which all agents *gather around* these shared graphs and interact among them by reading, writing and propagating the changes. The abstraction axis is hidden inside the agents and defines what parts of the graph are accessible by its internal components. This is discussed in recent works by the group [7], [12]. Figure 2 shows a schema of the RoboCog architecture by the time of the final demonstrations of the project.

When a mission is assigned to the robot it is internally re-coded as a desired state in an AGM graph, which could include the whole world or just the symbols needed to satisfy the mission. The Executive module is the one in charge of achieving it. The steps needed to transform the current AGM graph are provided to the Executive by the *Task-based Planning and Monitoring* module PELEA as a sequence of tasks that are injected back in AGM. At this point, AGM holds the current belief about the world and the current desire about how the world should be. Agents scan the graph and find tasks that can be performed by them. Inside each agent there may be some limited capability of planning or sequencing sub tasks, e.g., maintain the interest of the person through dialog, monitor the correct execution of a gesture, recognize her facial emotions, etc. The most basic components are in charge of sensor motor loops and normally execute their commands without interaction with other components.

VI. The use case

We now describe the use case that constituted the main goal of the project. It was defined in the ADAPTA's kick-off meeting. The first version of this use case is depicted in Figure 3. It can be textually described as,

> Gualzru is waiting in the Waiting area. It is now ready to start one of its tedious working days. The Waiting area is at the middle of an uncluttered corridor in a large shopping center. People usually enter this side of the mall from the left side of the corridor, crossing in front of the Panel area before entering the shops. People going out the mall also cross in front of the Panel area, but walking toward the left part of the corridor. The objective of Gualzru is to offer products and services to all these people. In fact, its aim is to drive potential consumers to an advertising panel, in which these products and services will be displayed. As there are products for everybody, it can choose any person in the corridor. When it chooses a target, it moves from the Waiting area following an intersecting trajectory with the person's heading direction. This displacement is very short (2-3 meters maximum) and allows Gualzru to wait for the person in a static pose, facing her at comfortable social distance (1,5-2 meters minimum). Therefore, Gualzru can say 'hello' to the person without scaring her even if she is not very used to interact with a moving robot.
>
> If the person engages with him in this first contact, Gualzru will classify her into a group -using gender and age parameters- and will choose a product topic to offer. Product topics provide Gualzru an specific theme of conversation before inviting her to walk back to the Waiting area. During this short conversation, Gualzru will be always ready to say goodbye to the user if she shows the intention of leaving the conversation or if the presented product topic is not interesting to her. On the other hand, Gualzru must also check its batteries level to say goodbye and move to the Charging area if this level is under a minimum value. The Charging area is close to the Waiting area. In fact, when Gualzru arrives to the Waiting area, he will home itself to the Charging area. If the person agrees on going with Gualzru to the Waiting area, both move there and the robot says goodbye to her. Then, it returns to the Waiting area and waits for some time, which is the expected time that the person is going to be at the panel, before starting the process to select a

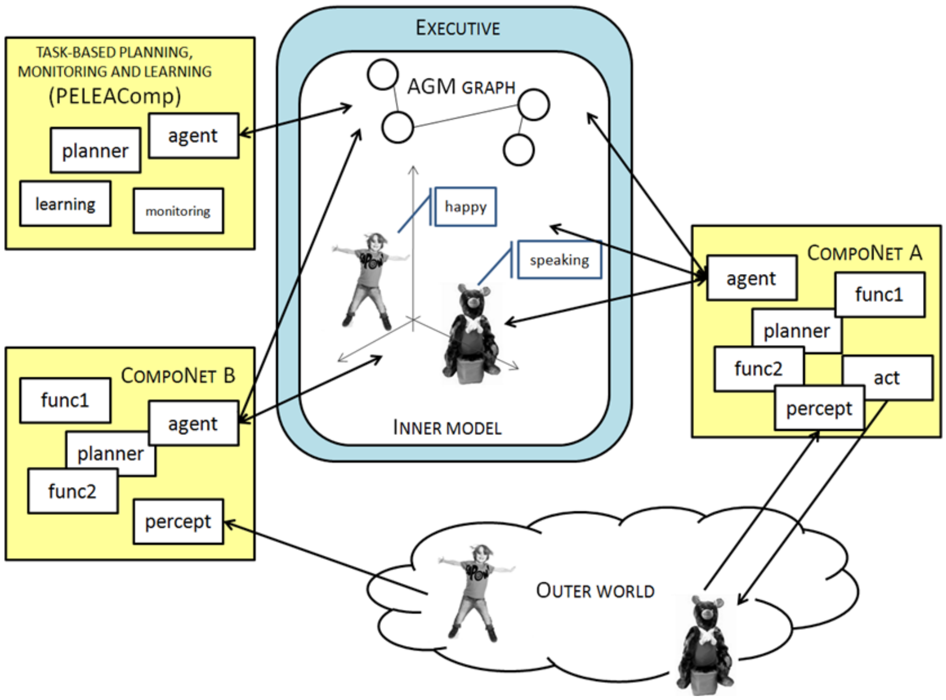

Fig. 2. An overview of the RoboCog architecture (from [16])

new target. As before, if batteries level are under a certain value, Gualzru moves to the Charging area for a reload.

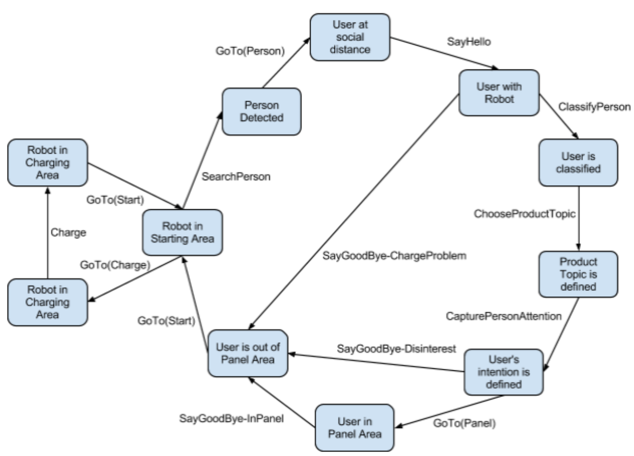

Fig. 3. The ADAPTA use case

VII. An annotated diary

As was mentioned before, the coordination of the project was based on periodic hackathons. We think this decision was a real success. We have already noticed the difficulty to integrate complex software and reach milestones without a real motivation from the people working in different labs. Many times, the global objective or the potential implications of the work are not correctly perceived. Other, personal relations get in the way. Hackatons have turned out to be an effective way to code, debug, test, share, make progress and build a team spirit.

A. May 2012. Kick-off

The project initiated with a kick-off meeting at Málaga where the overall strategy was discussed and the periodicity of the meetings was set.

B. December 2012. The "WORST" workshop at Cáceres

The main objective of the first hackathon was to explain and establish RoboComp as the common code base. All groups on the consortium had certain degree of knowledge about RoboComp, but it was considered mandatory to organize a workshop where simple examples could be programmed by all researchers under the supervision of experts from the Universities of Extremadura and Málaga. Fifteen people from all research groups and some more and some from Indra Software Labs met at Cáceres.

C. May 2013. First public demonstration at Málaga

For the first public demonstration of the whole project we had a simple prototype of Gualzru (Figure 4). Two autonomous behaviors were tested: the reactive navigation and a face detector. The AGM graph and the kinematic tree were able to internalize the perceived information. The seed of the architecture was planted. Obviously, not everything worked properly. The algorithms underneath both behaviors were changed in the final version, for example. But this fact was rather usual during the project. Other issues were more time consuming as expected. During 2013 we tried to replace the laser by

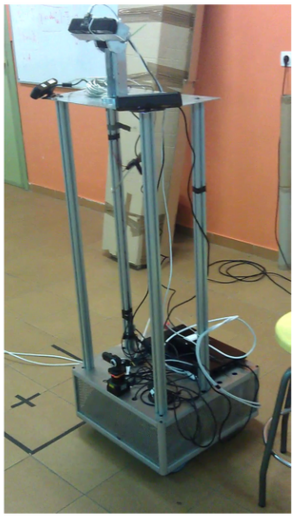

Fig. 4. The initial internal skeleton of Gualzru

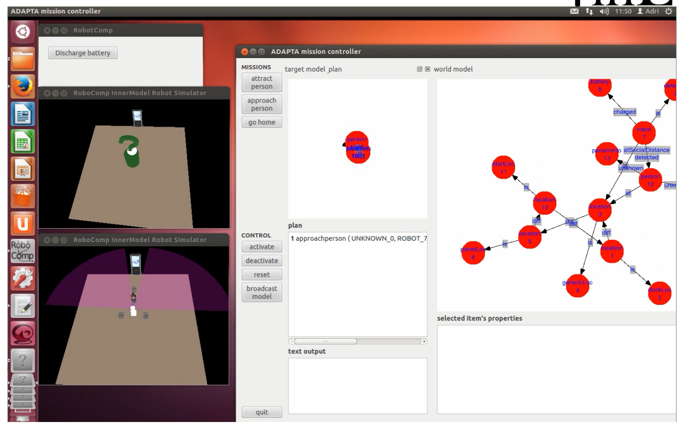

Fig. 5. Playing with the 'empty-boxes' architecture. The dashboard shows different panels: the one on the right shows the graph models that encodes (a) the goal to achieve -target model plan, and (b) the symbolic view of the outer world. It also includes the current action of the plan ('approachperson' in this figure). The panel on the left shows a visualization of the kinematic tree -up- and of the virtual world -down. We did not endowed the virtual robot with virtual sensors. The person is automatically detected if she is in front of the robot.

an array of RGBD sensors, arranged in a configuration that provided a wide field of view and theoretically gave good 3D coverage. Researchers from the Universities of Extremadura and Málaga were involved on achieving this goal. The sensor had limitations to perceive at short distances and we had to connect them to embedded computers like the Raspberry Pi of the time to liberate the USB ports in the main computers of the robot, Intel's NUC. We could not make the Asus' Xtion to run reliably with the available Raspbian. A few months after the end of the project, we succeeded with another board, the ODroid C1 [13], and now we can create hard-components that are cheap and provide real-time performance. We spent a few months trying to make that device work because we though it should work. Clearly, it was not the time. You have to choose the right battles.

D. November 2013. First evaluation of the architecture at Albacete

One of the major goals achieved after the meeting at Málaga was the development of a complete architecture able to work with a simulated robot in a virtual environment. The so-called 'empty boxes' architecture took this name from the fact that it included a complete version of the architecture RoboCog, although some of the components only had the public interface -IDL file- and the structure inside. Nevertheless, it included the two inner graphs -the symbolic and the geometric-, the conversational module, reactive navigation, person detector and high-level planning, executing and monitoring. To play with it we did not need the physical robot, but a computer with a RGBD sensor, speakers and a joystick. The simulated robot operated as an autonomous agent and we were able to move a virtual person in the simulator using the joystick. When robot and person were at interaction distance, the robot tried to convince the person to accompany it to the advertisement panel using his conversational skills. The speakers and the microphones on the RGBD sensor were used to support this interaction stage. The RGBD sensor was used to detect the face of a real person during the conversation. It was an intensive integration task.

One of the major successes of this architecture was the development of the triangle, high-level decision maker - executive - symbolic graph model. We were now able to translate to PDDL the information stored and updated in the symbolic graph (AGM) to the PELEA framework at the deliberative level. Furthermore, the Executive module was able to publish the graph to all software components on the architecture when a change was introduced. These components were arranged on networks, connected to the Executive through one distinguished component, the so-called agents. These agents were the responsible of maintaining the coherence of the information stored in the inner model, since they update the graph-model and, simultaneously, the geometric information of the kinematic tree. This second route was not supervised by the Executive. For the first time, the new definition of agent, included formally in the RoboComp component model and code generator, allowed all participants to share the graphs using the same interface. Our shared global representation on the state was now real and working.

We were able to launch more than fifteen software components. From this point of view, we were able to modify or add new components over a full-integrated architecture. Each successive meeting would imply a refinement of the previous proposal. While waiting for the robot Gualzru, see Section III for reasons explaining the long wait, we set up an old Nomad 200 robot with the RoboCog architecture and organized a new meeting at Albacete. See Figure 6.

At Albacete we evaluated for the first time the robot's behavior through questionnaires filled by the people interacting with the robot. The questionnaire is designed as a Likert scale, although it uses six levels, from 0 to 5, to remove the

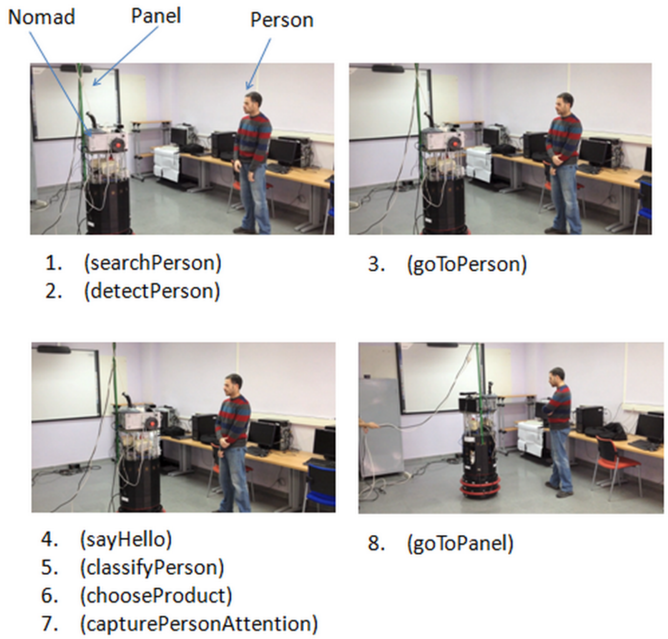

Fig. 6. The old Nomad performing through the use case at Albacete

TABLE II
QUESTIONNAIRE RESULTS (50 TESTS)

Question	$\bar{x}$	σ
1.1 Do you feel safe when the robot approaches you?	4.31	0.95
1.2 Does the robot invade your personal space?	0.96	1.37
1.3 Do you think robot movements are natural?	2.62	1.23
1.4 Have you stepped away from the robot?	0.96	1.46
2.1 Have you understood the robot?	3.57	1.28
2.2 Has the robot understood you?	2.70	1.30
2.3 Was the conversation coherent?	2.96	1.38
2.4 Do you like the voice of the robot?	3.13	1.29
3.1 Did the robot get blocked?	1.39	1.72
3.2 Was the interaction natural?	3.11	1.11
3.3 Was the conversation fluent?	2.85	1.22
3.4 Did the robot seem to be tele-operated?	0.87	1.44
4.1 Did you enjoy the experiment?	4.31	0.88
4.2 Do you think the exp. was not interesting?	0.70	1.32
4.3 Would you like to repeat?	4.28	1.32
4.4 Would you recommend it to other people?	4.52	0.86

neutral option -middle point. It is similar to that employed by Joosse et al. [15] to generate the database BEHAVE-II. Its main difference is that it has been created not from the point of view of the person observing the behavior of the user against the presence of the robot, but from the point of view of the same user that interacts with the robot. In this sense, we can consider that it collects influences of questionnaires of the Almere original model for man-machine interaction. In particular, the questionnaire includes a collection of questions arranged in four blocks: navigation, conversation, interaction and general sensations. The user fills the questionnaire giving a value for each response between 5 (completely agree) and 0 (completely disagree). These questions are listed in Table II. From that point on we would use that tool to evaluate the evolution of the project. Although at Albacete we were able to run the software in a real robot, we only could finish 12 use cases with different users. The number of questionnaires were also reduced to take hard decisions based on it, however the results were promising.

E. May 2014. Second public demonstration at Málaga

The Nomad 200 was moved from Albacete to Málaga and we continued testing specific problems related to the navigation module, speech generation and recognition, and person classification based on age and gender. The communication among components was forbidden and all information was transmitted through the inner representation. Things still did not work as we needed and the causes were not clear. Then, the robot Gualzru arrived and all efforts were translated to getting it ready.

For the second public demonstration Gualzru was already running RoboCog. Probably, this was not a mistake, but we did this integration without time to test the whole system. Also, we put the emphasis on collecting a larger collection of questionnaires. And to worsen things even more, the meeting was not set as the other previous hackathons: the goal did not focus on solving technical problems that were really there, but on showing a prototype that, at the end of the day, we should have known that it would not do the job. And the results were not good. During the demonstration the robot was able to interact with a person but it showed its limitations: the odometry alone was not able to correctly solve the localization problem, speech recognition had problems to work on crowed environments, the person classification module blocked the full use case until a good image of a face was taken, and so on. Another significant lesson was learned and never forgotten: you can not say that your robot will succeed in one trial until you have tested it for at least hundreds of times. There is a saying that can be applied here: ”let’s rehearsal so hard that the show looks like a rest”.

F. June 2014. Hackathon within the Workshop on Physical Agents

In June 2014, all groups had talks within the Workshop on Physical Agents (WAF2014) to be held in León (Spain). We asked the local organizers to facilitate us a working space to set up another hackathon during the week before. Vicente Matellán, the conference director gave us a cordial welcome and provided an excellent place for testing.

Before the hackathon, we discussed and organized the problems to solve there and when we arrived to León everybody knew what to do and joined in groups for a long week. The result was a real success: the dialog module was largely improved and tested, the localization problem was solved using AprilTags landmarks, and so on. The use case was repeated and repeated, and for the first time we detected real bugs and problems to deal with. After several days of intense work, Gualzru was able to do its job relentlessly until the battery was off! The robot spoke with all of us in the Lab and accompanied us to the panel. We had the impression that all ours problems were solved. We were happy for the moment...

But we were not going to enjoy the success for a long time. After discovering that the learning module would make the robot avoid people that always answered: 'No, I do not want to go with you to the panel', our host asked us to move Gualzru to the large hall where the conference was about to start and to have it welcoming the assistants. It looked like a good scenario for our use case. We accepted.

The moment we moved to the hall new problems appeared. The robot was unable to talk to people because nobody, not even humans, could hear what the other was saying. The space was wide open and we could not find a good place for the AprilTags landmarks. Light conditions were changing and the algorithms in charge of the RGBD camera did not always run correctly. For our younger researchers the experience was really hard, as they passed from the complete success to a glaring failure in a short time. Nevertheless, we were now in the final scenario. A spacious environment where the robot must interact with a specific person while other people are speaking and moving around. The failure had an aftertaste of an approaching victory. We still were able to close some use cases in this challenging scenario and a new time for improvements had started.

G. December 2014. Large evaluation test at Málaga

After a new demonstration at Ingenia (Málaga), in an environment very similar to the hall at León where we could capture new questionnaires, we returned to the Lab. The array of microphones of the Kinect sensor was intensively tested and, finally, we decided to change it for a shotgun microphone. As it is described with more detail in [12], other minor issues were also solved.

On December, 2014, the current version of Gualzru was tested in a real working scenario. The system was deployed in the hall of the Escuela de Ingenierías at the University of Málaga. The area where the robot was operating was about 70 square meters. Fixed obstacles included a column and some tables, but most of the area was free for the robot to move. The hall was populated by students and the trials lasted two half-days. The robot worked without human intervention and engaged with people passing nearby. These people had no *a priori* knowledge about the robot, nor its functionality. We collected a large set of questionnaires. The results are shown on Table II.

This data showed that the conversational system remained as the weak point of the robot. Some people did not correctly understood the robot due to the environmental noise and the voice of the robot was perceived as not particularly pleasant. But the most important issue was related to the understanding capabilities of Gualzru. Even when using the shotgun microphone these capabilities were strongly limited. The system is too sensitive to environmental noise and echos and it gets also confused when there are several people speaking around the robot. This situation is more common than expected due to the interest the robot produces. Additional issues such as different accents, voice volumes, etc. add more difficulties to the scenario. Despite these limited conversational skills, Gualzru achieved its main objective, to capture the attention of people. Most of them enjoyed the experiment and also would recommend the experience to friends or would like to repeat it. Comparing these results with the ones collected in the first experiments, revealed that successive updates in the robot have made it more robust and its conversational abilities, while still constrained, have been significantly improved.

H. Last stage: refining the HRI

The conversational abilities represented a severe drawback. Despite our efforts, only 50 % of the people that interacted with the robot in these real scenarios thought that it was able to maintain a coherent conversation. This was not enough for a robust, useful robot. But if you cannot solve a problem, perhaps is a good option to totally change the way to solve it. The speech recognition issue is hard to solve in noisy and crowded environments, where even humans find difficulties in understanding each other. Therefore, our idea was to look for alternative methods to allow people communicate with the robot. Speech recognition was reinforced with the incorporation of a tactile screen installed on the chest of the robot. The verbalized phrases were now displayed on this screen and it was possible for the person to answer the robot by touching it. This way, Gualzru retained its conversational abilities but the new interfaces increased its robustness and reliability. Following this modification, a new set of questionnaires were collected on the same scenario at the University of Málaga.

These questionnaires showed us that the mean values related to questions 2.1 and 2.2 (Table II) improved from 3.57 to 4.27 and from 2.7 to 3.72, respectively. Additional changes on the whole architecture allowed the robot to successfully close 93 % of the started use cases (on December 2014, this rate was 81 %). Furthermore, the unfinished use cases were always caused by the large amount of people in the place that would prevent Gualzru from reaching the panel.

VIII. Conclusions

In this paper we have presented the long process of creation of Gualzru, the salesman robot built for the ADAPTA research project. Looking at the starting requirements, we can firstly conclude that the final version of the robot conforms with the goals and expectations that we and the companies in the consortium initially had. But it is also true that even more rewarding than Ursus has been the whole process of collaboration and the knowledge distilled during these years. It is not that common that basic research is taken close to the *production line* while all the intermediate steps are registered and analyzed as a means to improve both, the forthcoming research and the methods and ways to generate reliable technology, given a limited amount of resources. For us, it has been a productive experience, both personally and professionally, and the capacity of the group to approach new technological challenges has increased notably. We have learned something useful in every step of the project, from the handcraft manufacturing materials and steps, to the way humans are starting to look at the (social) robots.

From the point of view of the technology that has been created and used in the project, we reaffirm the initial idea of the need for a common code base that brings together the work of all researchers. We still need some adjustments in the protocols and some refinements in the technology, and even more conviction by some doubters, but at the end of the day we might well be in the right track. The cost of maintaining and improving a framework like RoboComp is compensated by the flexibility of adapting it to your needs. Making good choices in this field, where Robotics meets Software Engineering, is not easy at all but once the software reaches a certain point of maturity, the leverage is undeniable. In the near future, we believe that these frameworks will play a crucial role in the evolution of intelligent robots. A role much more important that it is given today. It is needed the confluence of interested people from Software Engineering to gradually introduce new advances in DSLs, meta-models, model-based design and communication middlewares. From the recent evolution of social robot software, it looks like to us that the near future will bring larger and finer-grained networks of components, hundreds within the next years, that will demand more efficient software communications, self-diagnosis and repair, and sophisticated monitoring and deployment systems. Maybe classic, coarse-grained architectures will meet fine-grained ones at a point where interaction dynamics play a relevant role.

The cognitive robotics architecture, RoboCog, is a much more experimental and uncertain piece of handcraft. We started with a standard three-tier schema and managed to integrate symbolic planning with a fair amount of perception and action. To get there we re-introduced the idea of a shared representation among modules playing the role of an explicit context. It was implemented as two graphs, one geometric and one symbolic, and it proved enough for the required advertisement scenarios. Also, the introduction from the beginning of symbolic planning and learning technology in the project has proven a huge success. The initial idea of a using a flat PDDL description of the domain with a standard planner has evolved now into HRI specialized schemes, where hierarchical planners take care of quotidian, repetitive tasks and flat ones of the fine details and contingencies that might occur [19]. But, each solution takes to the next problem and before the end of the project, we were already working on integrating both graphs, reordering the classical hierarchies into more versatile organizations, infiltrate lifelong learning into all crevices of the system or use domain specific symbolic planning in classical low-level modules like navigation or object recognition. This issue, dealing with the overall organization of robotic intelligence, is undoubtedly the hardest one but projects like this motivate, and ultimately enforce, the search for new theoretical perspectives.

Other crucial part of the global Gualzru experience has been the use of evaluation metrics. User questionnaires turned out to be very important to improve the people's attitude towards the robot, as well as to reveal the most urgent weaknesses in preliminary stages. It is a valuable lesson to be kept that periodic tests and surveys are an important part of HRI research, although they are often seen by roboticits as a dull, questionable use of the scarce human resources available. Another important source of feedback are the robotic contests like RoboCup@Home[2] or RoCKin[3], that put all teams in the track of a common goal, and where real performances are evaluated in front of expert judges.

The ADAPTA project officially finished on May 2015 with a final public demonstration in Málaga. There Gualzru was able to interact with many people and successfully closed several difficult use cases. All partners in the consortium were satisfied and the robot will be serving from now on at the headquarters of Indra in Madrid. The research groups are now involved in more collaborative projects that hopefully will fund the construction of new social robots. We hope that the next generation will be capable of providing a better service to humans.

Acknowledgments

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