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Mobile Manipulation Hackathon: Moving into real world applications

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***Abstract*— The Mobile Manipulation Hackathon was held in late 2018 at the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) to showcase latest applications of wheeled robotic manipulators. The challenge had an open format, where the teams developed their chosen application for a specific robotic platform, using simulation tools and afterwards integrating it into the robotic system. This paper presents the competition and analyzes the results, with information gathered during the competition days and from a survey circulated among the finalist teams. We provide an overview of the mobile manipulation field, identify key areas required for further development to facilitate the implementation of mobile manipulators on real applications, and discuss ideas on how to structure future hackathon-style competitions to enhance their impact on the scientific and industrial community.**

I. Introduction

Autonomous mobile manipulation combines two fundamental robotic skills: mobility in the environment and manipulation of objects. The ability to do both simultaneously opens numerous applications in diverse areas including manufacturing, logistics, home automation and healthcare. Such applications typically require complex (structured and unstructured) manipulation. They also require navigation in large spaces, possibly in cooperation or close interaction with human beings or other robotic systems.

Mobile manipulation is a complex field. Mobility introduces additional pose uncertainty to the manipulation problem, while limiting the available perception systems and introducing additional constraints to the navigation problem that now needs to also consider one or more arms mounted on the robot. Mobile manipulation is also a systems challenge, requiring the designer to draw on multiple different fields: perception, navigation, task, path and grasp planning, control, error recovery, human-robot interaction, and robotic hardware development. Each field is an area of research in its own right, but the particular challenge in mobile manipulation is to obtain an integrated system that can combine a large variety of hardware and software components to increase the range of tasks that the robot can perform, while decreasing the dependency on prior information and increasing the awareness the robot has of its current situation.

As the complexity of mobile manipulation lies at the interface of the different fields mentioned above, and any significant experimentation will not only require mastery of a variety of techniques but system integration and acquisition of hardware, it is difficult to establish mobile manipulation as a field of its own. Similarly, it is not clear what the commercial applications of mobile manipulation really are. While performing truly human-like tasks is only possible when combining mobility and manipulation, the high cost and limited performance emphasize commercial solutions that are either only mobile, such as floor cleaning or transport, only manipulation, such as conventional robotic assembly lines, or constrain the system in such a way that manipulation remains trivial, for example picking up and transporting entire shelves in warehouses. However, other applications such as telepresence and remote assistance systems are moving toward demanding some way to remotely interact with objects and persons, for instance in elderly assistance scenarios. Also, industrial scenarios might be able to solve multiple tasks with fixed-base manipulators, but a single, flexible mobile platform could autonomously take over multiple tasks in different locations, thus possibly improving the return on investment of the robot, especially important for the case of small and medium enterprises (SMEs) that cannot afford multiple static robotic platforms.

To address these challenges and build a community around mobile manipulation, the IEEE Robotics and Automation Society (RAS) Technical Committee (TC) on Mobile Manipulation together with their members and collaborators organized a "Hackathon" — a word combining "hacking" and "marathon" — that gives common ground to participants by providing a complete mobile manipulation system offering a basic level of operation. This allows the community to showcase (1) their work in relevant sub-fields such as grasping, manipulation, perception or motion-planning, and (2) application domains that might truly benefit from a mobile manipulation solution.

The hackathon phenomenon has been described in the context of digital innovation as an appropriate vehicle to

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bring people from different disciplines together as well as to actually engage the community with a particular topic [1]. Consequently, a body of work exists on how to design a hackathon to optimize the desired outcome in terms of networking [2], learning [3], or broadening participation in computing [4]. In its purest form, the hackathon format therefore brings groups of unrelated people together to share knowledge and work towards a solution, learn from each other, and potentially form long-term connections.

Given the current state of the art in hardware and software, we deemed it unlikely of getting significant insights from an ad-hoc event in which teams are formed at the conference venue, with no previous contact or chance to learn about the available tools. Instead, the Hackathon has been organized as a multi-staged competition from which finalist teams were selected based on an initial entry mostly based in simulation results.

Related hackathons and competitions

Robotic competitions have very similar aims as a hackathon, but operate with a different time scale (months of preparation vs. a single day, for example) and emphasize robust solutions above prototypes. Competitions have a long history in robotics and artificial intelligence with their entries often determining the state-of-the-art for years to come, such as in localization [5] or autonomous driving [6]. They can also lead to unexpected insights on what the problems in a systems challenge really are. For example, the Amazon Picking Challenge [7] has shown that warehouse picking is less of a grasping and manipulation challenge (the majority of teams used suction) rather than a perception problem. Similarly, the Industrial Assembly Challenge [8] has shown that perception and planning are secondary when dealing with sufficiently restricted and well-defined problems.

Despite much progress in these research domains, open-loop control as well as mechanical templates and fixtures usually excel in such scenarios. These insights can then be used to refine the competition format to push the community in a desired direction.

Many successful competitions focused on robotic manipulation have been organized in recent years. The Robotic Grasping and Manipulation Competitions have been organized at IEEE IROS 2016 [9], 2017, 2019 and 2020[1] (online). They included a fixed set of tasks, for example Service tasks (such as spooning peas, or preparing iced tea), Manufacturing tasks (assembly/disassembly), and Logistics tasks (bin picking). The tasks did not require mobility. The Real Robot Challenge[2] is organized by the Max Planck Institute for Intelligent Systems (MPI-IS) in 2020. This competition is based on remote execution of submitted software on a robotic hand hosted at MPI-IS. There is a fixed set of tasks such as grasping and pushing, which do not require mobility. The IEEE Int. Conf. on Soft Robotics (RoboSoft) also holds a competition[3] with a manipulation challenge that focuses on soft manipulators. Similarly, the tasks do not require mobility.

There have also been recent competitions that target mobile manipulation. The FetchIt! Mobile Manipulation Challenge was held at the IEEE Int. Conf. on Robotics and Automation (ICRA) 2019 [10]. The task was to assemble a kit formed by six objects obtained from stations around a designated arena, combining navigation and manipulation skills. Similarly, the RoboCup@Home competition[4], using the Toyota HSR [11] robot as the official platform, includes a set of tidying up or service tasks in living room or kitchen set ups, which require mobile manipulation. The RoboCup@Home also encourages teams to make "Open Challenge" demonstrations (i.e. free demonstrations determined by the teams, instead of the fixed set of tasks), though these open demonstrations are not the main focus, they are performed at off-hours of the competition, and therefore the "Open Challenge" award is not necessarily awarded [12]. The SciRoc Challenge [13], which is organized as part of the European Robotics League and builds on the success of the European Robotics Challenge (EuRoC) [14], also includes a fixed set of mobile manipulation tasks, such as delivering coffee shop orders, and shopping pick and pack.

The unique feature of our Hackathon, compared to the competitions above, is that it brings *mobile manipulation* together with *open demonstrations* at the center stage. As explained above, recently there have been multiple mobile manipulation competitions that focus on a fixed set of tasks. This has the advantage of creating benchmark tasks that enable measuring progress objectively. Therefore, such benchmark competitions are crucial for the community. However, we believe an open format also has its place among competition formats: It allows (a) the teams to demonstrate their core research innovations more directly, and (b) the community/audience to get informed about the state-of-the-art for a rich variety of tasks. With the Mobile Manipulation Hackathon, our goal has been to push the teams to perform their own research demonstrations, to identify the tasks that the research community is working on.

In this article, we explain the structure of the Mobile Manipulation Hackathon that was hosted together with the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS) in 2018, discuss the applications developed by different teams and their performances, while presenting an overview of the current state of mobile manipulation. Based on these observations, we discuss system advances that are needed to enable even more fertile multi-day hackathons, as well as lessons learned on how to structure future hackathons to improve our understanding of the specific challenges and applications of mobile manipulation.

II. The Field of Mobile Manipulation

Bringing together mobility and manipulation, mobile manipulation systems need to overcome some of the most difficult challenges in robotics:

[1]https://rpal.cse.usf.edu/competition_iros2020/
[2]https://real-robot-challenge.com/
[3]http://www.robosoft2019.org/robosoft_competition.html
[4]https://athome.robocup.org/

- Generality: Mobile manipulation systems must perform a variety of tasks, acquire new skills, and apply these skills in novel situations. They must be able to continuously adapt and improve their performance.
- High dimensional state space: Versatile robotic systems must be equipped with many actuators and sensors, resulting in high-dimensional state spaces for planning and control.
- Uncertainty: The ability to locomote, the required generality in task execution, and the usage of multiple sensors and actuators, make it impractical to engineer the entire environment for the task. As a result, mobile manipulation systems have to explicitly address problems that arise due to the uncertainty of sensing and actuation.
- System complexity: Mobile manipulation systems require the integration of a large number of hardware components for sensing, manipulation and locomotion, as well as the orchestration of algorithmic capabilities in perception, manipulation, control, planning, etc.

The mobility of these systems can take multiple forms depending on the environment: air/space (drones, planes, helicopters, satellites), water (ships, submarines) or land (wheeled, legged robots). In the air/space, mobile manipulation systems often take the shape of an aerial vehicle carrying some sort of manipulator [15], [16], e.g. a gripper [17] or a multi-link arm [18], [19] attached to a rotorcraft, or a manipulator endowed with some flying mechanism, e.g. rotors [20]. A significant challenge for these systems is to maintain flight stability during object manipulation, which limits the range of manipulation operations that can be performed. This coupling between the control of mobility and manipulation also exists in the water, where the robot needs to maintain a stable pose while experiencing additional forces due to object manipulation [21], [22]. Land is the most common environment for mobile manipulation. Humans live on land and, therefore, a larger variety of mobile manipulation tasks can be found here. Furthermore, the control of mobility and manipulation can be decoupled more easily on land, when compared to in-air or underwater manipulation: A land robot can attain a statically stable configuration and, for small enough forces, not worry about balancing during manipulation.

Two common forms of mobility on land are legs and wheels. Legged locomotion and bimanual manipulation are typically combined in humanoid robots, e.g. [23]. Even though planning and control for legged locomotion can be more complex than for wheeled locomotion, legs can be advantageous depending on the ground characteristics. Particularly for search and rescue operations, where debris, obstacles, and steps on the ground are expected, legged mobile manipulation is preferred. Such systems dominated, for example, the DARPA Robotics Challenge [24].

The most common and versatile mobile manipulation systems, however, are wheeled systems. Wheeled systems strike the right balance between ease of mobility and manipulation, and access to most human environments. The development of wheeled mobile manipulators has spawned over the last three decades and a half. The first prototype of a mobile manipulator was MORO back in 1984 [25]. The first relevant attempts to mount robotic arms on mobile platforms happened during the 90s, with robots such as HERMIES [26], and KAMRO [27]. The particular problem of coordination of base and arm motions also had seminal contributions on these years [28], [29]. Since then and over the last three decades there have been many developments and highlights in wheeled manipulation systems. Hvilshøf et al. surveyed up to 30 different prototypes developed until 2011 [30]. The main application domains of mobile manipulation systems ranged from domestic service [31], [32] through space [33] to industry, with commercial solutions from e.g. KUKA[5] or NEOBOTIX[6].

Around 2010 a wave of more advanced, bi-manual multi-purpose wheeled manipulators started (Fig. 1) with systems such as the PR2 [32] developed at Willow Garage, the Care-O-bot 3 [34] developed at Fraunhofer AIS, HERB [35] developed at CMU, Rollin' Justin [36] developed at DLR and the ARMAR series developed at KIT [37]. This wave represented a milestone since it coincided with the introduction of ROS (Robot Operating System) [38] to the community, which, through its modular structure and components such as the ROS Navigation Stack[7] and MoveIt![8], made it easier to build the complex software systems controlling these robots. 2010 was also the year when the IEEE-RAS Technical Committee on Mobile Manipulation was established.

Though this series of wheeled manipulation systems have created a lot of excitement and interest in mobile manipulation and its applications over the years, it also revealed the challenges. The cost of building such systems was especially prohibitive for large scale use and adoption, hampering the development of a larger research community. Early adopters of mobile manipulators were the military and law enforcement areas, who used robots for dangerous missions including bomb defusal or remote inspection of installations. In the last few years a rise of simpler yet fully integrated and commercially-oriented wheeled manipulation systems has been observed. These developments include TIAGo[9] (unimanual) and TIAGo++ (bimanual) by PAL Robotics, Fetch Mobile Manipulator[10] by Fetch Robotics (available for researchers), Swift[11] from IAM robotics, RB-1, RB-Kairos, RB-Eken and RB-Vulcano systems from Robotnik[12], industrially-oriented KUKA KMR[13], and assistance-oriented

[5] https://www.kuka.com/en-gb/products/mobility/mobile-robots
[6] https://www.neobotix-roboter.de/produkte/mobile-manipulatoren
[7] http://wiki.ros.org/navigation
[8] https://moveit.ros.org/
[9] http://pal-robotics.com/robots/tiago/
[10] https://fetchrobotics.com/robotics-platforms/fetch-mobile-manipulator/
[11] https://www.iamrobotics.com/our-solution/
[12] https://robotnik.eu/products/mobile-manipulators/
[13] https://www.kuka.com/en-gb/products/mobility/mobile-robots/kmr-iiwa

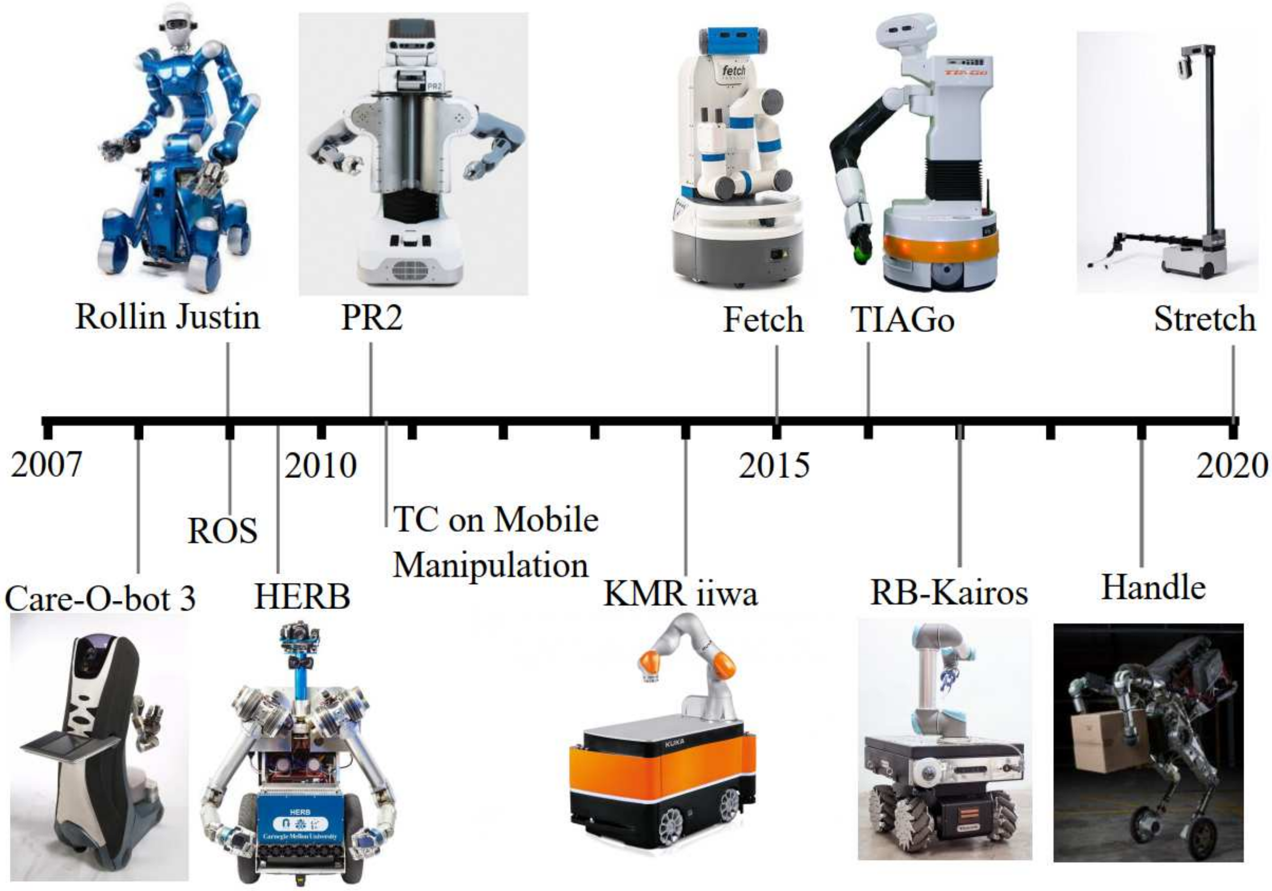


Fig. 1: Timeline for development of wheeled robotic manipulators in the last decade.

Toyota HSR[14]. The field is still in evolution, and interesting concepts have been recently presented, such as Handle[15] from Boston Dynamics, and Stretch[16] from Hello Robot. Fig. 1 presents a timeline of development of these wheeled robotic manipulators. These systems target applications such as part supply and transport in manufacturing and logistics, and object transport and human-interaction in healthcare and personal care. Yet the mobile manipulation market is still a niche, and estimations of the market for this type of systems are difficult to obtain. For instance, the latest report from the International Federation of Robotics does not include mobile manipulation systems as a separate domain but rather combined in the overall statistics according to application areas (industrial, logistics, medical, field robotics, defense, etc.) [39]. However, it is recognized that the combination of mobile platforms with collaborative robots opens the door to solve new use cases and could substantially increase the demand of robotic systems.

With the advances in development of mobile manipulators and its wide potential of applications, comes the need for standardization, especially in topics related to safety in cases of human-robot collaboration. There have been recent important efforts in this direction, even though there is still uncertainty about regulations covering the use of mobile manipulators. Depending on the area of application different regulations apply. For example, in industrial settings many integrators apply both ISO 10218-1 about Safety of industrial robots and ISO/TS 15066 about Collaborative Robots when the manipulator of the mobile robot is in action, and they apply either ISO 3691-4 or former EN 1175-1:1998 when the robot navigates by keeping the arm static to prevent conflicts between the aforementioned norms. More recently, the American National Standard (ANS) published the ANSI/RIA R15.08-1-2020, targeting specifically safety requirements for industrial mobile robots. On the other hand, healthcare applications may require ISO 13482 about safety requirements for personal care robots.

III. Mobile Manipulation Hackathon

The Mobile Manipulation Hackathon was conceived to encourage participants to implement demonstrations that showcase the applicability of a wheeled robotic manipulator. The call was open to contributions from any field (e.g. learning by demonstration, grasp planning, human-robot interaction) or domain (e.g. logistics, healthcare, service), as long as they could be integrated into a predefined robotic platform to execute a mobile manipulation application. The selection of

[14]https://www.toyota-global.com/innovation/partner_robot/
[15]https://www.bostondynamics.com/handle
[16]https://hello-robot.com/product

Fig. 2: Wheeled manipulation platform TIAGo.

the application and the final script of the demonstration were proposed by the participant teams. The Hackathon organizers evaluated and filtered the most promising and appropriate proposals to ensure that they fitted the scope and purpose of the activity.

This methodological approach is different to most other competitions that are based on detailed task descriptions for the participants to solve. In our experience, these approaches have the main drawback that they deliver overfitted and engineered solutions to the specified tasks that are not easily generalizable and therefore usually have low impact on the associated research fields. In an open domain such as mobile manipulation we feel that this is not effective. As an alternative we propose an open format in which teams can demonstrate their knowledge on tasks proposed by them.

Mobile Manipulation Platform

In order to ease and motivate the participation on the Hackathon we proposed a common mobile manipulation platform, TIAGo by PAL Robotics[17]. It is endowed with a 7 DoF arm, a liftable torso, and a pan-tilt head equipped with a RGB-D camera and stereo microphones (Fig. 2).

Participants in the Hackathon benefited from the completely ROS-based interfaces, and a simulation environment to develop, in their own labs, an initial proposal for their demonstration. The demo was required to necessarily and effectively use the potential of a mobile robot (e.g. the proposed demonstration could not be solved with a fixed-base manipulator only). Participants could exploit the ROS tutorials and demonstrations publicly available[18].

Applications developed in simulation were later implemented on the real robot with the support of PAL Robotics researchers and engineers. PAL Robotics sponsored the competition by lending three TIAGo robots, available on-site during the final event. In addition, selected teams were allowed to spend a week testing and tuning their demonstration at the PAL Robotics site the month before the final event.

Competition procedure

The participation in the Hackathon was an activity that had to be prepared well in advance. With this purpose we designed a procedure that gave the teams enough time to develop their proof of concept, and the organizers enough time to set up the selection procedures. The procedure consisted of the following milestones.

- Call for participation (Early 2018). An announcement was distributed in several mailing lists with descriptions of the Hackathon scope, goals, procedures and timeline.
- Expression of interest (March 2018). Interested parties submitted a letter introducing the team and presenting their proposed application and demo, background, planned use of equipment, etc.
- Feedback to teams (April 2018). Organizers provided suggestions on how to create a high impact demo.
- Entry Submission (June 2018). Teams submitted a video and a short technical report explaining in detail their proposed demo and their original approach/technology to be showcased at the Hackathon. At this stage, simulations were allowed in the video.
- Announcement of finalists (July 2018). Six finalists were selected from all the submissions. The selection criteria included maturity of the development, novelty and relevance of the specific components, and relevance of the application.
- Support in Barcelona (September, 2018). Finalist teams were given the opportunity to test and tune their demos on the robot for one week at PAL Robotics headquarters.
- Competition (October 1-5, 2018). The final event took place during the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS) in Madrid, Spain. The event lasted three days, and two teams participated each day. Teams were given the whole day with the robots on-site to prepare their demonstration, which was presented in the late afternoon. A committee of three international experts comprised of Prof. Jeannette Bohg from Stanford University, Dr. Graham Deacon from Ocado Technology and Prof. Weiwei Wan from Osaka University, evaluated the demonstrations. The criteria for the evaluation were novelty, academic merit, industrial merit, quality of the integration and impressiveness of the demonstration. The winners were announced at the end of the third day.

Competition results

Thirteen teams submitted entries. These teams came from countries worldwide (India (2), Germany (2), Spain (3), Switzerland (1), Singapore (1), Japan (1), Brazil (1), Mexico (1), USA (1)) and proposed an extensive variety of ap-

[17] `http://pal-robotics.com/robots/tiago`
[18] `http://wiki.ros.org/Robots/TIAGo`

Team name	Affiliation	Country	# Members	Demo
Homer Team	Koblenz University	Germany	2	Imitation learning of human actions `www.youtube.com/watch?v=Pf91wv2ddQE`
Robotics.SG	Nanyang Technological University, Panasonic R&D Centre Singapore, Hand Plus Robotics, and Panasonic Connected Solutions Company	Singapore	6	Item placing in an e-commerce warehouse `www.youtube.com/watch?v=_3wZ3J6NWCc`
IRI	Technical University of Catalunya/Spanish National Research Council	Spain	3	Adaptive robotic feeding assistance `www.youtube.com/watch?v=dM9DoZ2z6To`
PMM Tohoku	Tohoku University	Japan	5	Dexterous liquid pouring in a domestic situation
TAMS	Hamburg University	Germany	5	TIAGo as a bartender `www.youtube.com/watch?v=AOkhmyDtDfQ`
IOC-AUDECO	Technical Unversity of Catalunya/Institute of Industrial and Control Engineering	Spain	10	TIAGo serving drinks `www.youtube.com/watch?v=VocnVbh5Nq8`

TABLE I: Finalist teams.

plications, as listed below (some applications were proposed by several teams).

- Imitation learning of manipulation tasks
- Robotic home assistant
- Robotic assistant in a hospital
- Robotic feeding assistant
- Autonomous mechanic assistant
- Autonomous librarian
- Autonomous bartender
- Gardening applications
- Item picking in logistics scenarios

The six finalist teams are described in Table I, and pictures of their demos are shown in Fig. 3. A video overview of the competition is publicly available[19]. Due to the high quality of the demos, the jury decided to select two winners, teams TAMS and Robotics.SG. Their demos were:

- Team TAMS: implemented a software system that converted TIAGo into a bartender, pouring drinks and cocktails to clients from behind a counter (Fig. 4). The robot recognized a person sitting in a predefined location on the other side of the counter, and approached them to take their order. The robot instructed the person to point to their favorite drink on a typical cocktail menu, detected the menu's pose on the table via keypoint detection, and extracted the person's fingertip via contour detection and heuristic filtering. The robot could detect if the person was trying to fool it by pointing elsewhere but one of the drink names. Once the desired drink was identified via deictic interaction, the robot proceeded to a separate table where the liquor bottles were stored, and created a composite manipulation plan to retrieve the required ingredients, transport them and pour them one after the other in a transparent glass in front of the customer. The glass was identified using the IR image of the RGB-D camera. A composite motion plan was generated to pour a specific amount (parameterized by duration) into the glass, without spilling during the reaching motions.
- Team Robotics.SG: the robot was used to re-shelve products that were returned to a convenience store (Fig. 5). The robot picked up a tray with the returned items, identified the objects inside the tray (verifying as well that the tray was not empty), and planned the required motions to put the items back in the corresponding shelf. During setup, the robot scanned and pre-stored a map of the area, including the location of items on the different shelves. The item identification was performed using a pre-trained learning-based perception approach, which also delivers the pose of the object. The acquisition of images for training the perception system was performed using an in-house developed rotatory platform to scan the shape and texture of the object. Once an individual object pose was defined, a grasp motion was planned to pick up the item. Checkpoints were defined to verify if a grasp was successful or not. The robot then navigated to the required shelf to place each item at its intended location.

[19] `www.youtube.com/watch?v=mt7JGXHb8jQ`

IV. Survey of the Competition

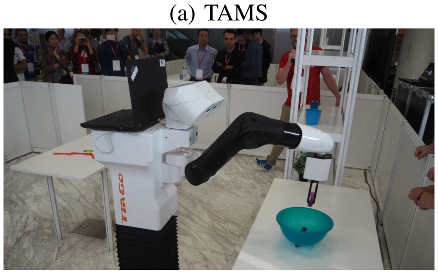
To compare the effort for the competition and its relation to the research performed by the team, we distributed the following survey via email to the finalist teams. The survey contained 19 questions, and the answers were provided in free text format.

1) Team survey
   a) Team name
   b) Institution(s)
   c) Number of team members (include breakdown by academic degree)
   d) Previous experience in competitions
2) Development process
   a) Did you develop the system from scratch? (if not, provide a previous publication if possible)
   b) Estimated time of demo development, in person months
3) Demo/system description
   a) Description of the demo
   b) Sensors used for the demo (tactile, vision, microphones, etc.)
   c) Hardware adaptations/additional tools for the demo
   d) Software framework
   e) Simulation tools

(a) TAMS

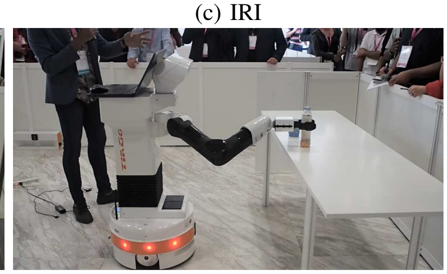
(b) IOC-AUDECO

(c) IRI



(d) Homer Team

(e) Robotics.SG



(f) PMM Tohoku

Fig. 3: Demos of the finalist teams in the live competition.

Fig. 4: Snapshots of demo execution for the TAMS team. From left to right: user pointing to the menu for choosing a drink, TIAGo moving to the bar for retrieving one of the required liquors, and TIAGo pouring the (real) liquor on the glass.

Fig. 5: Snapshots of demo execution for the Robotics.SG team. From left to right: TIAGo retrieving the bin with the returned items, TIAGo navigating the store using a pre-recorded map, and TIAGo placing one of the items on the required shelf.

f) Motion planner
g) External libraries/dependencies
h) How much autonomy did the robot have? (full autonomy, shared autonomy)
i) Type of control
j) Was there interaction with humans? (tactile, voice, etc.)

4) Takeaways
a) Which components of the system caused you the most trouble during the competition?
b) Did you evolve the demo after the Hackathon? (include reference to publications as an outcome of the demo, if that is the case)
c) What is the most important lesson taken from your participation in the Hackathon?

Team survey

Among the finalists, five were university teams, while one was a mixture of institutions (university, research institution and companies). As a condition to enter the Hackathon, we limited the number of team members to 5; however, the survey reported that the real number of individual contributors was between 2 and 10. All the teams had some combination of PhD and M.Sc. students, and some teams included supervisors (postdocs/professors), technicians or undergrads. From all the participants, 15% were postdocs or professors, 45% were PhD students, 35% were M.Sc and undergrad students, and 5% were technicians.

Four out of the six finalists had some previous experience in other competitions, including the European Robotics League, RoboCup, European Robotics Challenge, Amazon Robotics Challenge, World Robot Summit, DJI Mobile Manipulation Challenge, and Nvidia Jetson Challenge. However, previous experience was not a guarantee of success, as one of the two winner teams reported no previous experience in robotics competitions.

Development process

All the finalists based their demonstration on previous work, either scientific (papers or PhD theses) or technological (platform/software components developed for other competitions). Four of the teams had at least one mobile manipulation platform in their labs. The estimated time for preparing the specific Hackathon demo strongly depended on the previous experience of the team, ranging from 1 to 9 full person months. Note however that this estimation of efforts is just indicative, as it was recalled after the actual competition.

Demo/System description

The demos shown on the final round were a mixture of interactive and non-interactive executions. All of the demos were fully autonomous, and required human intervention only for solving certain failures (e.g. objects out of reach, failures in self-localization, or unintended collisions). The three non-interactive demos focused on completing tasks that required some sequence of object perception, manipulation, and navigation. The Homer team demonstrated autonomous picking and sorting of cutlery after a party (the objects were randomly placed on the table) using semantic scene reasoning, as the objects were not easily identifiable using only depth information. A guarded motion was used to grasp the cutlery by first touching the table in a pre-grasp pose and then closing the fingers to grasp the object. Suitable checkpoints were provided to verify whether the grasp had been successful. The object was then placed in a bowl located in a different table. The process was repeated until the table was clean. The robotics.SG team showed a re-shelving application, as described above. The PMM Tohoku team demonstrated a liquid pouring task, with detection of the transparent bottle and container. This detection was based on simple segmentation techniques, fitting a plane to the table, removing it and then fitting cylinders to the remaining clusters of points (which represented the bottle and cup).

The other three teams required some interaction with humans. Team IRI showed a robot capable of feeding impaired humans in a safe and delicate manner. The demo used an Amazon Alexa 3G interface to request commands, e.g. choice of food, and human detection to find and interact with the person. The robot transported the food and placed it in the table in front of the person. An arm-mounted camera allowed the robot to detect if the human was interested in eating (when the human looked toward the camera), and when this happened, it retrieved food with a spoon. Then, if the robot detected that the person opened the mouth, the person was fed. The process continued until the person indicated to the robot that no more food was required. After this, the robot removed the food from the table (and politely said goodbye to the person). Team TAMS showed a bartending application, as described above. Team IOC-AUDECO also showed a drink serving application. In this case, the robot would first perceive the drinks available on a cluttered table, and the human could choose the desired drink among the available ones using a tablet or keyboard. Then, the robot would plan a manipulation sequence to retrieve the desired drink from the table; the plan included moving away cans that were obstructing the path to grasp the desired drink. A randomized physics-based motion planner introduced in [40] was used for this purpose. This planner permits robot-object and object-object interactions such that when there is no collision-free path towards the object to be grasped, no explicit high-level reasoning of the task is required, but possible complex multi-body dynamical interactions are evaluated using a physics engine, and considered in the expansion of a sampling-based planner. In particular, the planner enhances the state validity checker, the control sampler and the tree exploration strategy of the KPIECE kinodynamic motion planner [41].

The teams based their demos mainly on the hardware and sensors available on TIAGo. Team IRI additionally required a 6-DoF force torque sensor to guarantee a safe feeding to the human. They also developed their own special 3D printed gripper adapters for assuring an easy and stable grasp on the cutlery. Apart from these upgrades, the capabilities of TIAGo for carrying out a collision-free navigation and arm motion planning were used. Team IOC-AUDECO used a 4-fingered Allegro hand instead of the default 2-finger gripper, to show more advanced grasping capabilities. Team TAMS required an additional HD webcam on top of TIAGo, to get an image with enough resolution to detect the desired drink from the menu. Team Singapore.SG added a portable table to the robot to be able to carry the tray with the returned items. Additionally, they modified the shelves so that their lower part was perceived as a solid obstacle by the laser scanner used for navigation (otherwise, the shelf would have been missed, as the four legs are thin).

In terms of software, the developments were mainly based on ROS, as all robot interfaces were tightly integrated with this framework. Simulations and visualizations mostly employed Gazebo. All the teams created specialized modules for certain tasks required for their demo, and some teams relied also on additional libraries. Team IRI used OpenFace[20] for face recognition, and OpenPose[21] for person detection. Team IOC-AUDECO implemented planning in clutter using the Kautham Project[22]. Team TAMS used the MoveIt Task Constructor[23], developed by some team members and fully integrated in ROS, to define and plan actions consisting of multiple interdependent subtasks. Team Singapore.SG used YOLO[24] for object perception, which was trained using images obtained with a self-built acquisition system [42]. The Homer team reused custom mapping and navigation tools[25] previously developed for other robotic competitions. They used Mask-RCNN[26] for object detection and segmentation, which combined with planar surface segmentation, helped to detect the cuttlery.

For control, most teams relied on open-loop position-based execution of planned sequences, followed by a verification stage using TIAGo's sensors (joint encoders, vision) to decide if the plan was executed as intended. Team IRI used a force-based control loop to control the robotic arm while the feeding action was in progress. Team Koblenz integrated continuous current measurements into the grasping approach to detect contact with the table. Interestingly, no team used visual servoing techniques for controlling the manipulation actions. This indicates the focus on restricted scenarios with quasi-static assumptions or that explicitly required human cooperation.

Takeaways

We asked the teams to identify the most troublesome components for their demonstration. Each team could identify any number of challenging areas; Fig. 6 summarizes the responses. The most problematic area was object detection.

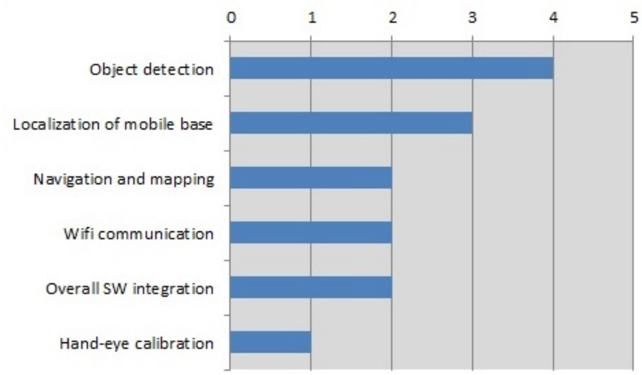


Fig. 6: Challenging areas in the Hackathon demos.

Interestingly enough, on a survey performed on the participants of the Amazon Picking Challenge [7], perception was also identified as the most difficult component in the competition. Different techniques were employed by the teams for object detection and pose estimation: based on features, CAD models or surface textures, learning-based detection and estimation, and registration based on fusion of depth and RGB data. In some cases, challenges came from the detection of transparent objects (bottles, glasses).

Localization of the mobile base was ranked as the second most challenging area. To cope with localization problems, for instance, team IOC-AUDECO relied on Aruco markers to enhance the robustness of the table localization. Team Robotics.SG wrapped paper around the shelves legs to facilitate mapping, navigation and localization of the mobile base.

We were also interested in finding out if the experience gained from the Hackathon was exploited afterwards in some way, or if it was an isolated effort. From the four teams that provided an answer to this question, three indicated that they evolved some of the components used in the demo either to create a more advanced lab demo (teams IOC-AUDECO and TAMS), or to reuse some solutions for a new competition (Homer team). The demo from team TAMS, for instance, was transferred to a different platform, a PR2 robot, thus showing the generality of their solution[27]. Three of the teams (IRI, IOC-AUDECO and TAMS) indicated that some of the demo components were further developed and were already published or are submitted for publication as scientific papers. The IRI team has been able to transfer the knowledge gained with the force loop controller used in the feeding task to a new scenario involving bimanual cloth manipulation [43]. The IOC-AUDECO team continued the development of the task and motion planning for mobile manipulation executions [44]. The TAMS team further developed the perception of objects used in the competition, to detect and reconstruct transparent objects [45].

We finally asked the teams what was the most important lesson they learned from the Hackathon. Team IRI highlighted the need for further supervision during the demo

[20] https://cmusatyalab.github.io/openface/
[21] https://github.com/CMU-Perceptual-Computing-Lab/openpose
[22] https://sir.upc.edu/projects/kautham/
[23] https://github.com/ros-planning/moveit_task_constructor
[24] https://github.com/pjreddie/darknet/wiki/YOLO:-Real-Time-Object-Detection
[25] https://github.com/homer-robotics
[26] https://github.com/matterport/Mask_RCNN
[27] https://www.youtube.com/watch?v=8S2MvKNbwmM

execution. They report that as a lesson-learned, their current demos are now carefully designed to accommodate double-check control at different levels of their execution. In this line, team IOC-AUDECO identified the need for more robust error detection and recovery strategies to resume tasks and recover from unexpected situations during executions. Team TAMS highlighted the benefits of integrating independent components in a unified demo, and recognized the need for intensive testing of each component before the integration to avoid more difficult debugging of the overall execution. Team Homer appreciated the benefit of having on-site robotic platforms for implementing the demo out of their original lab, thus reducing funding needs and transportation/insurance costs for the participating teams. Also, they highlighted the benefits of having a common robotic platform for increasing comparability of results across multiple research groups.

V. Discussion and Outlook

In this final section we discuss the lessons learned after organizing the Hackathon, and the outlook for similar future events.

Hackathon structure

The Mobile Manipulation Hackathon challenged the community to show integrated demos that exploited the benefits of a mobile robotic manipulation platform. This required development and/or integration of components at different levels, e.g. perception, navigation and localization, grasp and manipulation planning, human-robot interaction.

The teams were free to propose a demo script, and they used this opportunity to showcase not a fixed task, but their latest developments in the above mentioned fields. This was a key difference of our Hackathon, when compared with competitions where the task is fixed. We believe both types of events are beneficial for the field: competitions with a fixed task provide a more clear picture of the progress on that particular task. Competitions with an open-task structure, such as ours, are useful to understand the variety of possible applications. Therefore, we encourage the community to, and we intend to, organize both types of competitions in the future.

Use of a fixed demonstrator platform

The opportunity to use a unified HW/SW platform based on ROS provided the chance to compare multiple approaches. A solid software and simulation framework allowed the teams to remotely develop their demo, thus reducing the time required for physical integration in the robotic system. However, we recognize that the basic tools for fast prototyping and quick debugging still need to be enhanced to enable integration of full systems with few days of access to the demonstrator platform. In terms of the competition, it was greatly beneficial to have the robots on-site, thus relieving teams from the burden of worrying about transportation costs, insurances, basic set up and infrastructure, and allowing them to focus on the pure development process.

From the perspective of robot manufacturers, the Hackathon was also a great opportunity to gather valuable feedback from both experienced and novel users of the robots, which helps to improve how the next generation of robots is conceived. The research community can also benefit from this kind of competitions to identify tools, libraries and frameworks that could help accelerate the implementation of real-world applications with complex robots like mobile manipulators. As an example of this, one of the perspectives for mobile manipulators is the adoption in the coming years of ROS2, which will provide better and more efficient data distribution among processes, support to coordination of multiple robots, security, real-time control, among others.

Applications of mobile manipulation

Mobile manipulators are becoming increasingly available, and have a huge potential to provide cost-effective solutions in different scenarios, including for instance industrial automation, manufacturing, logistics, healthcare, teleassistance, and crop harvesting. In many scenarios, robots will replace humans in dull, dirty, dangerous and difficult tasks, for instance in bomb disposal operations or handling biological samples, as demanded now in times of pandemic. But as we saw during the Hackathon, a huge potential also lies in collaborative applications, where robots either try to efficiently share their workspace or physically cooperate with humans in a delicate manner. Pouring liquid into a glass, serving a drink or feeding a person are clear examples of it. More interesting and complex applications with autonomous bi-manual, rigid or deformable object manipulation tasks can be even considered if more than one mobile manipulator is simultaneously used, or if a dual arm mobile manipulator is employed.

Further technical advances required

As mobile manipulators are complex systems that encompass different areas, they benefit from advances in those fundamental topics, including perception, localization and navigation, and overall software integration and reliability, which we also identified as critical topics in our competition results (Fig. 6). Some of the challenges are platform-dependent, including for instance robustness in communication (robust and reliable wireless communications are required), integration of third-party hardware and/or software, and kinematics (e.g. simplicity to obtain a closed-form inverse-kinematics solution). On the other hand, some other issues can be considered as general mobile manipulation difficulties, including the following:

- Localization: precise location procedures within the robot's environment.
- Perception: robust identification of the objects and estimation of their poses, using different sensors, including hand-held cameras for visual-servoing purposes.
- Grasping: automatic determination of grasp configurations taking into account the scene.

- Motion planning: capacity of planning collision-free motions as well as motions that require contact, in order to perform push actions.
- Task planning: automatic determination of the sequence of actions to perform the manipulation task; it may include regrasping actions and the need to simultaneously consider the planning of the motions.
- Reasoning: need of reasoning capabilities to understand the situation and accordingly tune all the previously stated issues.
- Failure detection and recovery: Use of reasoning capabilities for failure detection and selection of recovery strategies.

If robots are to enter more complex scenarios such as a warehouse, grasping and manipulation capabilities must be greatly improved, as robots must show capabilities to handle a huge variety of products in terms of size, weight, textures, rigidity, located in different types of containers, bins or shelves, especially in densely packed or cluttered scenarios. This requires naturally further integration of tactile sensing, visual servoing, and in general fusion of multiple sensing modalities to enhance the awareness of the robot.

As the competition called for system-level demos, a successful execution depended on multiple components running simultaneously. Inevitably, failure rates multiply in such complex scenarios, and success requires a heightened awareness of failure sources and handling of non-prototypical situations. In other words, reliability of the platforms must be enhanced, and they must be endowed with advanced error detection and recovery capabilities.

Speed of execution is also a pending topic. During the Hackathon demos, the robots took several minutes to perform actions that a human could do in a matter of seconds. Autonomy while working on batteries was not an issue with the demos, as they were relatively short (below 10 minutes in total for a full run), but it will be critical in real applications where the robots must be available during extended periods of time.

A proper exploitation of the whole-body coordination to simultaneously employ the mobile base and the manipulator while performing the intended task is also required [46]. This has not only implications in terms of how to effectively use the multiple DoFs and redundancy of these platforms, but also in terms of standardization and certification, essential to guarantee safety for applications of such systems especially in human-robot collaborative scenarios.

The issues above (i.e. multi-modal perception, manipulation planning and reasoning, system-level integration, speed of execution, and whole-body coordination) continue to be the main challenges in mobile manipulation systems, as also observed during other recent mobile manipulation competitions [10], [11], [13]. A more recent development is the introduction of competitions that focus on learning-based approaches, e.g. the Real Robot Challenge by MPI-IS in 2020. This follows the general trend of merging Robotics and AI, but these competitions currently focus on manipulation-only tasks, as opposed to mobile manipulation. Far more challenging than fixed-based manipulation, mobile manipulation holds the potential for being a disruptive advance in robotics for applications at multiple levels, from industrial to home and healthcare environments. Open-challenge hackathons/competitions targeting mobile manipulation would continue to serve the field and the community in the future.

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