Development of a Dexterous Dual-Arm Omnidirectional Mobile Manipulator[⋆]

Raúl Suárez[*] **Leopold Palomo-Avellaneda**[*] **Jordi Martinez**[†]
Daniel Clos[†] **Néstor García**[*]

[*] *Institute of Industrial and Control Engineering (IOC),*
[†] *Mechanical Engineering Department,*
[*†] *Universitat Politècnica de Catalunya (UPC), Barcelona, Spain*
e-mails: {raul.suarez, leopold.palomo, jmartinez.miralles, daniel.clos, nestor.garcia.hidalgo}@upc.edu.

Abstract: This paper presents an experimental mobile manipulator composed of a dual-arm torso with a human-like structure assembled on an omnidirectional platform. The dual-arm system integrates several commercial devices: two arms UR5 with 6 degrees of freedom, each one equipped with an Allegro Hand with four fingers and a total of 16 degrees of freedom, and each fingertip provided with a tactile sensor. The omnidirectional platform has a circular shape and three wheels, with an original special design, whose coordinated movements allow omnidirectional displacements of the platform. It is equipped with laser-range sensors, a radio positioning system and an RGB-D camera to detect potential obstacles and navigate safely. The paper describes the main aspects of the mechanical structure of the mobile manipulator and the software framework developed to control the whole device.

Keywords: Robotics, Mobile Manipulators, Dual-Arm Robots.

---

1. INTRODUCTION

Robotics is getting a larger space in more and more fields and applications, and different kinds of robots are being developed for each of them. The large variety of robots ranges from traditional industrial robots to complex and sophisticated humanoids, but real applications quite frequently do not need, or cannot be efficiently solved by, such extreme types of robots, thus many other types of robots are being developed. A typical case is the need of mobile manipulators, which, from the practical point of view, are usually addressed by simply installing one (or more) manipulator arm on a mobile platform, frequently using wheels that could be of different types depending on the desired performance and the expected conditions of the environment. The robot presented here follows this approach, we intend to have a human-like torso with two arms and dexterous manipulation capabilities able to move around mounted on an omnidirectional platform.

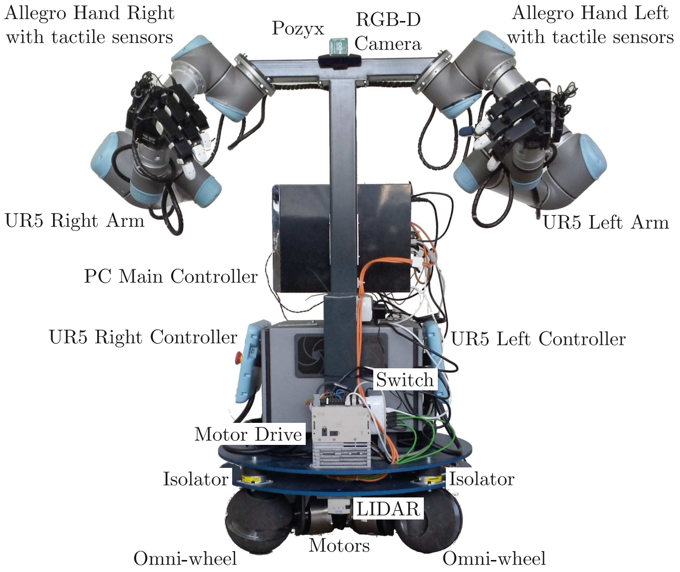


Fig. 1. Front view of MADAR.

The developments regarding mobile manipulators that can be considered as antecedents for this work started with a mobile platform with only one robotic arm on it (Khatib, 1999) and now several new commercial devices have this structure, e.g. Tiago from PAL Robotics. On the other side, dual-arm robots with human-like morphology were also developed, e.g. Justin (Albu-Schöffer et al., 2007) and TOMM (Dean-Leon et al., 2017), and there are already some commercialized devices, e.g. static, YuMi from ABB and Baxter from Rethink Robotics, and mobile, Pioneer Manipulator from Adept. This type of devices generates new perspectives regarding the human-robot collaboration when the devices have intrinsic security due their mechanical design and control systems (Reitelshöfer et al., 2014). In order for these type of devices to be of utility in different environments, they must have a high degree of autonomy, thus they must have planning capabilities, both at motion and task level.

This paper presents a general purpose dexterous dual-arm mobile manipulator named MADAR (from Mobile Anthropomorphic Dual-Arm Robot), shown in Fig. 1, which is composed of commercial arms and dexterous hands assembled on an omnidirectional mobile platform

---

[⋆] This work was partially supported by the Spanish Government through the project DPI2016-80077-R. N. García is supported by the Generalitat de Catalunya through the grant FI-DGR 2018.

specifically developed using a new type of wheels, which is one of the relevant original contributions of the work.

The reason that motivates the development of the mobile robot presented here is the need of a completely open platform to perform experiments in the fields of planning and control in mobile and dexterous manipulation, merging the know-how of the group in grasping, manipulation and motion planning and extending it to the mobile case and the interaction with human operators.

After this introduction, the remaining of the paper is organized as follows. Section 2 introduces the omnidirectional mobile base, describing the omni-wheels designed for the platform and its control, and Section 3 describes the human-like dual-arm dexterous structure assembled on it and the control framework. Finally, Section 4 concludes the paper with the conclusions and the future work.

2. OMNIDIRECTIONAL MOBILE BASE

High maneuverability mobile platforms have been widely used in the design of mobile robots (Bischoff et al., 2011) as well as in other applications, like AGV, wheelchairs or forklifts (Adascalitei and Doroftei, 2011), being the movement inside reduced spaces one of the main conditioning.

Basically, there are two main approaches in the development of mobile platforms. The first one is based on the use of conventional wheels. Many different configurations are possible, combining different types of wheels: free-rolling or driving wheels, steering-controlled wheels or caster wheels The advantage of this kind of platforms is the simplicity in the wheel design, but their movements are non-holonomic (Barraquand and Latombe, 1989), which makes difficult their maneuverability and control, and they usually present less than three degrees of freedom (DOFs) in their plain movement.

The second approach consists of using non-conventional wheels or omni-wheels. This kind of wheels presents a specific sliding direction fixed to the platform, implemented by means of free-rolling elements, and a horizontal rotation controlled by a motor. The platforms equipped with omni-wheels dispose of the three degrees of freedom associated to the plain movement, without needing any steering wheel. Moreover, their behavior is holonomic if the movement is constrained to displacements without rotation of the base. These properties make their control easier than the control of other platform designs. Examples are the well known *Mecanum* wheel widely used in commercial applications (Fig. 2a), and the use of spherical omni-wheels composed of semi-spherical rollers (Fig. 2b).

The platform developed for the mobile robot presented in this paper follows the second approach and uses a new design of omni-wheels (Clos and Martínez, 2015). The following subsections describe the new type of wheels, how they are fixed and actuated in the mobile base.

2.1 New omnidirectional wheel

The developed wheel is based on spherical omni-wheels composed of spherical sectors and rounded-shape rollers with free-rolling movement (see Fig. 3). Each wheel is driven by a motor that produces a controlled rotation around a horizontal direction. The configuration of the wheel components defines a circular profile normal to the controlled rotation axle so that the wheel can rotate without sliding around this axis, meanwhile the free-rolling movement of the components simulates a horizontal sliding direction normal to the circular profile.

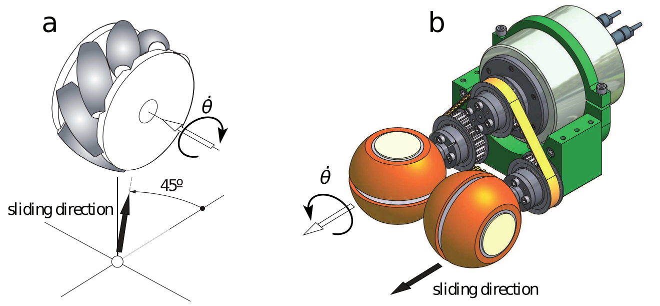


Fig. 2. Omni-wheel designs: a) *Mecanum* wheel with rounded-shape free-movement rollers; b) Spherical omni-wheel with truncated semi-spherical rollers in parallel configuration.

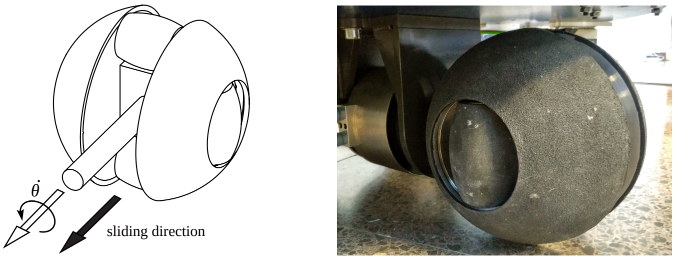
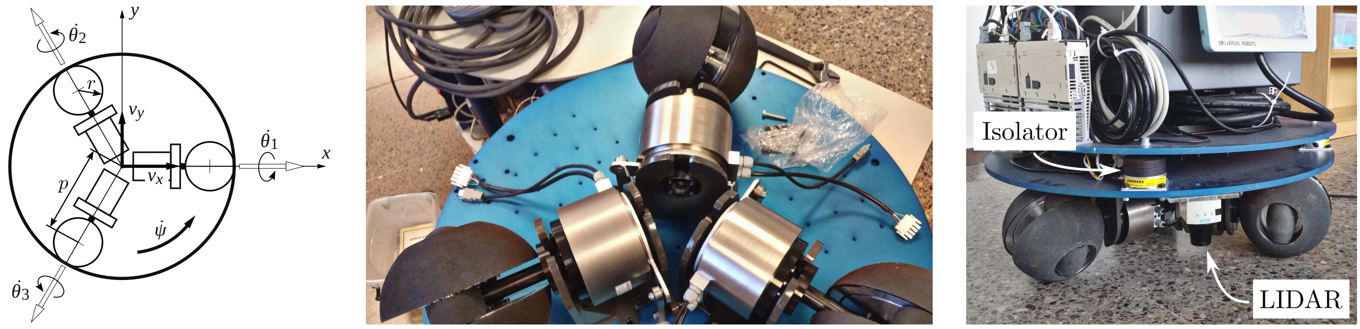


Fig. 3. Omni-wheel developed for the mobile base.

Looking for robustness, all the wheel components, spherical sectors and rounded-shape rollers, are made of aluminum alloy with a thin elastomer coating to get good grip with the floor. The use of steel axles and high charge capacity roller bearings allows the wheels to support without any problem the platform weight. This is relevant because the weight of the whole device is about 250 kg. The wheel diameter, 200 mm, assures enough room for the bearings and axles, and also allows to overcome small irregularities on the floor or small obstacles as, for instance, electric wires lying on the floor. The platform is designed to carry the dexterous dual-arm system described in Section 3.

The advantages of the proposed wheel design compared with other omni-wheels are:

- The location of the wheel-floor contact points is fixed with respect to the platform, and thus the control matrix components are constant (the matrix is detailed below in Subsection 2.2). In platforms using *Mecanum* wheels this location changes continuously during the movement, which makes the platform control more difficult, affects the platform odometry and produces parametric vibrations due to the continuous changes in the contact force application point.
- The conventional spherical omni-wheels (shown in Fig. 2b) present a singular configuration when the free rolling direction is normal to the floor (Batlle and Barjau, 2009; Batlle et al., 2010). So, in order to avoid this singularity, it is necessary the use of twin spherical wheels with truncated poles and perpendic-



a b c

Fig. 4. a) Base layout with the velocity coordinates definition, b) Detail of the mounted wheels and motors on the bottom, and c) Detail of one of the isolators and one of the LIDAR sensors between the base discs.

ular free rotations, both driven by the same motor. In this way, the contact force is exchanged between both wheels twice at each wheel turn, generating parametric vibrations in the platform. Moreover, the wide gap between the two semi-spherical rollers of the same wheel, necessary to allow the torque transmission by means of the motor shaft, is another vibration source due to the impacts that produces. The proposed wheel overcomes all these problems.

Some authors (Ferriere and Raucent, 1998; Runge et al., 2014) have proposed designs with entire spherical wheels inspired in the design of the mechanical computer mouse, but these proposals have been only implemented in light platforms with low charge capacity and low driving torques, due to the difficulties associated to the design of the link between the platform and each wheel.

2.2 Base platform and actuators

The base platform is circular with a diameter of 78 cm in order to allow the mobile robot passing through standard doors (see Fig. 4a). Three traction groups are located under the base, each one composed of a wheel and a motor, disposed in radial directions at 120 degrees of each other (see Fig. 4a and 4b). Using three wheels ensures a permanent contact between each wheel and the floor without needing any suspension systems or articulated frames. Moreover, the three degrees of freedom of the platform can be controlled by means of the three independent wheel rotations $\dot\theta_i$, simplifying the platform control.

Despite the advantages of the developed wheels, the mobile manipulator still suffers some vibrations produced by the fluctuation in contact forces inherent to the rolling movements of the hard surface of the wheels contacting the floor. In order to reduce the transmission of these vibration from the wheels to the upper structure, the motors and the omni-wheels are mounted on an aluminum disc (see Fig. 4b), and the robot structure with all their components are mounted on another aluminum disc, and vibration passive isolators were used to decouple both discs (see Fig. 4c). The space for the batteries and the power converter is also located between the two aluminum discs. In order to show the effect of these isolators, Fig. 5 shows the power spectra of the vertical vibration velocity measured at the upper dual-arm system while the mobile robot was moved along x-direction forwards and backwards, without isolators (red line) and with isolators (green line), it can be observed how the isolators reduce the vibration level and move the frequency bandwidth to lower frequencies. In the first case, the RMS value of the vibration velocity is 10.1 mm/s, in the second case this value decreases to 6.1 mm/s.

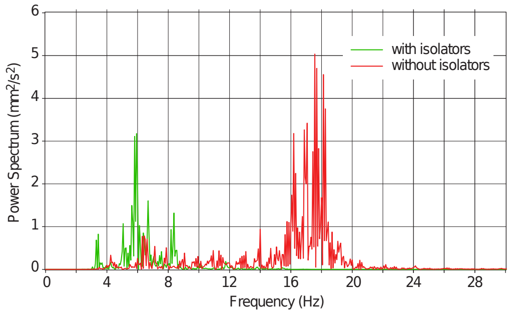


Fig. 5. Power spectra of the vertical vibration velocity measured at the torso base: without isolators (red line) and with isolators (green line).

For the actuators, direct-drive brush-less motors with high motor torque were used in order to avoid the need of gear boxes or any other type of transmissions. In this way, the rotation control of each wheel is not affected by gear backlash or mechanical clearances. The chosen actuators were Yaskawa Motors SGMCS-05B that incorporates a high-resolution 20-bit absolute encoder, without multi-turn data. These Direct Drive motors fit well in the design due to their compact form: a cylinder with 135 mm diameter and 88 mm length. Despite the small size, they can provide an stall torque of 5.15 Nm and an instantaneous peak torque of 15 Nm, which is enough for the (de)acceleration phases. For the motor control, the drive SGD7S from the same manufacturer was chosen. This drive can receive references of position, velocity and torque. The control strategy is run in an on-board computer, and the drive and the motor act all together as a black-box. The communication between the drive and the computer is done through EtherCAT (Ethernet for Control Automation Technology), an Ethernet-based Fieldbus protocol. Specifically, we use an OpenSource implementation of EtherCAT called SOEM [1], which provides almost all the functionalities of the protocol.

The control routines must run in the computer with minimum latencies to allow the motors working coordinately to generate a desired base trajectory, thus it is necessary to

---

[1] `github.com/OpenEtherCATsociety/SOEM`

run a Real Time Operating System (RTOS). In our case, a GNU/Linux with Xenomai[2] has been used. Xenomai provides a patch for the Linux kernel transforming it into an RTOS using a dual kernel approach, and, in our implementation, SOEM was adapted to run with it[3].

2.3 Control of the base movement

The velocity of the base during a movement on a planar surface, described by the components of the linear velocity of the platform center, v_x and v_y, and the angular velocity $\dot{\phi}$ of the base, is related to the velocity of the wheels, $\dot{\theta}_i$, $i = 1, 2, 3$, as

$$\begin{Bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{Bmatrix} = \frac{1}{r} \begin{bmatrix} 0 & -1 & -p \\ \frac{\sqrt{3}}{2} & \frac{1}{2} & -p \\ -\frac{\sqrt{3}}{2} & \frac{1}{2} & -p \end{bmatrix} \begin{Bmatrix} v_x \\ v_y \\ \psi \end{Bmatrix} \tag{1}$$

where r is the wheel radius and p the horizontal distance from each wheel center to the base center (see Fig. 4a).

Then, the desired base movement is obtained with coordinated motions of the wheel motors. It should be remarked that, with these wheels, the robot movement is holonomic if it is only translational and it is non-holonomic if the movement produces a base rotation (i.e. a change in the orientation of the base). For holonomic movements the final positions of the motors with respect to the initial ones fully determine the final location of the base, while, in the case of non-holonomic movements this is not enough, and it is necessary to integrate the base velocity during the movement in order to determined its final location. In both cases the odometric information could be taken into account to improve the computation of the base pose.

The control software of the platform has two remarkable C++ libraries:

- *cpp4Ec*: it encapsulates all the SOEM functions and lets the user work independently of the type of drive, either using position, velocity or torque commands. Thus, the developer works with a blackbox having an updated state of the motors using the SOEM functions without caring about the exchange of information between the RT and non-RT parts of the software.
- *libplatform*: it encapsulates all the functionalities related to the base, isolating them from the real hardware. This library lets the programmer to concentrate on the control algorithms for the base movement, allowing to command the base trajectories considering the motors and their controllers as black boxes. The library also uses odometry data to compute the current position during the movements.

2.4 Base location and obstacle detection

In the real world, the presence of functional sliding in the wheel-floor contact, as well as the presence of irregularities in the wheels and the floor surfaces, introduce positioning errors, making necessary an external position control loop.

The platform has two systems to obtain information about the environment and to detect its absolute position and orientation:

Fig. 6. Detail of the left robotic arm and hand.

a) A *pozyx* sensor[4]. It provides 3D positioning and motion information using wireless radio technology to identify the robot location with respect to a set of beacons fixed in known positions in the environment, thus, it is used to identify the robot location in its working environment (note that it cannot be used in any environment without the corresponding beacons). It has a maximum error of 10 cm, but in practice the usual error is significantly lower. The *pozyx* device is connected to the on-board computer using USB. It also has a high precision accelerometer, a gyroscope, a magnetometer and a pressure sensor.

b) 2D Laser Imaging Detection and Ranging (LIDAR) sensors. The system is composed of three TIM-561 sensors from Sick[5], mounted at 120 degrees of each other around the circular platform, each one in the middle of two wheels (see Fig. 1 and 4c). It provides information about the environment around the robot, in order to detect obstacles as well as to help in the robot localization. Each sensor has a field of view of 270 degrees, and therefore the combination of the three sensors allows obstacle detection all around the robot with redundant measurement in some areas. Each sensor operates from 0.05 m to 10 m with an angular resolution of 0.33° and a scans rate of 15 Hz. The maximal systematic error (precision) is 60 mm and the statistical error (repeatability) is 20 mm.

3. THE HUMAN-LIKE DUAL-ARM DEXTEROUS STRUCTURE

The dual-arm dexterous structure is assembled on top of the mobile base, the main components are the two arms and their controllers, the hands with tactile sensors, and a PC for planning and control (see Fig. 1 and 6). The arms are attached to a central metal structure with T-shape. The design gives to the robot a human-like height with a larger wingspan, allowing the robot to work in human environments, for instance, operating on a table or picking items up from a typical bookshelf and move them around. The heavy parts have been mounted trying to keep the center of gravity of the robot as low as possible for stability reasons. Fig. 7 shows the main robot devices and a diagram of the communication connections.

---

[2] `www.xenomai.org`

[3] `github.com/iocroblab/soem`

[4] `www.pozyx.io`

[5] `www.sick.com/de/en/detection-and-ranging-solutions/2d-lidar-sensors/tim5xx/tim561-2050101/p/p369446`

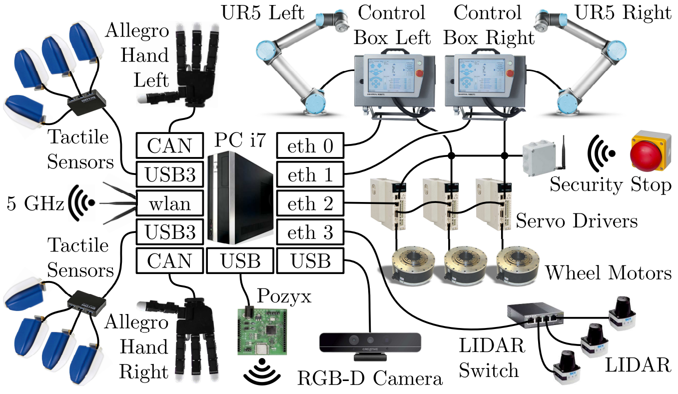


Fig. 7. Hardware elements with and their communication interfaces.

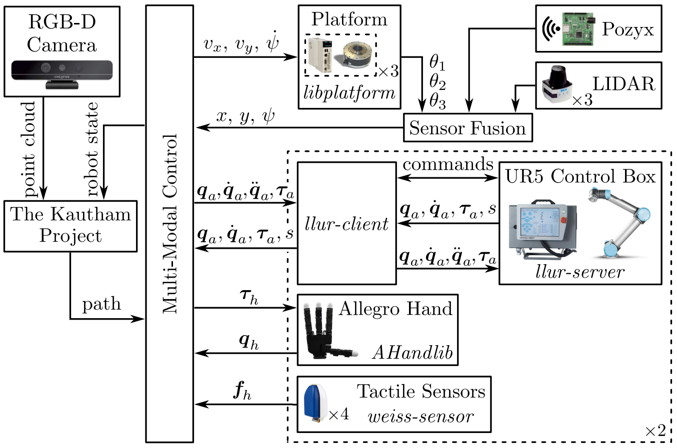


Fig. 8. Software elements of the mobile manipulator.

3.1 Arms and hands

The mobile robot is equipped with two industrial robotic arms UR5 from Universal Robots[6]. These arms have 6 DOFs, can hold up to 5 kg, and have collision-detection capabilities that allow a safe human-robot interaction. They have been assembled emulating the human-arm configuration (see Fig. 1) and such that, when the arms are folded, they fit within the circular area of the base, so that the robot can pass through standard doors and elevators. The arms have a working radius of up to 0.85 m and they are mounted 0.53 m apart and oriented to obtain a suitable overlapping of the two arm-workspaces, as well as a good manipulability value (Kurazume and Hasegawa, 2006) in front of the robot, where it is expected to perform most bimanual manipulations.

Each arm is equipped with an Allegro Hand from Simlab[7] as the end-effector. The Allegro Hand has four fingers and sixteen independent torque-controlled joints (4 joints per finger) and it is able to hold up to 5 kg. The hands can be controlled by position, velocity and torque, at a maximum frequency of 333 Hz, using a CAN interface. Each fingertip is provided with a tactile sensor WTS-FT 0408 from Weiss[8]. Each sensor has a sensing matrix with 8 x 4 cells, includes the complete signal processing electronics and transmit the data at 400 Hz via USB.

The control of the hands and the treatment of the tactile information is done using home developed libraries. This libraries were used to do grasps of bulky objects using the two hands (Rojas-de-Silva and Suárez, 2016) and are currently used to implement dexterous in-hand manipulation strategies (Montaño and Suárez, 2015, 2018).

3.2 Control and coordination of the dual-arm structure

All the elements of the dual-arm structure are controlled by a software layer running on the central PC attached to the T-shape metallic part that holds the arms. Each element is controlled by an isolated library, so they can work independently.

The arm positions, velocities and torques are controlled using the commercial CB2 control box. The manufacturer provides a library (*ur_c_api*) which allows a (limited) access to the low-level control, disabling the default interface and giving access to positions, velocities and torques of the arm joints at 125 Hz. The authors have developed a specific application (Low Level UR server, *llur-server*) using the manufacturer library), which is executed in each robot controller and establishes a communication through Ethernet with another application (Low Level UR client, *llur-client*) running in the central PC (see Fig. 8). In this way, each CB2 control box only runs low level routines (*llur-server*) and the control strategy requiring high load computation (*llur-client*) is done in the central PC.

Three communication channels are established between the server and the client using network sockets. One is devoted to communication control, where the *llur-client* sets the control mode (position-, velocity-, acceleration- or torque-control) and can ask to the *llur-server* for a report of the robot state when the robot status is not correct. In the second channel, the server acts as a *Publisher*, sending periodically, every 8 ms, the current joint positions $\boldsymbol{q}_a$, velocities $\dot{\boldsymbol{q}}_a$ and torques $\boldsymbol{\tau}_a$, and a flag s indicating whether the robot status is correct or not. On the client side, there is a *Listener* that is continuously listening and updating the internal variables describing the robot state. In the third channel, the client acts as a *Publisher*, sending asynchronously the commanded references to the robot. In the server side, there is a *Listener* that, according to the received commands, updates the arm references. Although there is a delay in the communication, about 12 ms, the obtained experimental results are quite good even when all the elements are working simultaneously. There are other approaches tackling the UR5 arm control, as ROS industrial[9], but they produce a higher delay, up to 160 ms.

Regarding the hands, the manufacturer only provides a simple driver using a CAN library for the communications, and they only accept commanded torques, $\boldsymbol{\tau}_h$, and return the positions, $\boldsymbol{q}_h$, of the joint encoders. On the other hand, the tactile sensors provide the distribution of forces $\boldsymbol{f}_h$ sensed at the fingertips. Therefore, two controllers have been specifically developed, one to control the finger movements when moving in the free space, and another to control the finger forces when grasping an object.

---

[6] `www.universal-robots.com/products/ur5-robot`

[7] `www.simlab.co.kr/Allegro-Hand.htm`

[8] `www.weiss-robotics.com/en/produkte/tactile-sensing/wts-ft-en`

[9] `rosindustrial.org`

3.3 Overall control and coordination

All the devices making up MADAR are connected to and controlled by the on-board central PC (see Fig. 7 and 8 for the communication and control schemes, respectively). Besides, the robot can also be remotely controlled using the 5 GHz wireless connection of the central PC.

A multi-modal control layer continuously reads the robot state and properly commands the wheels, arms and hands to follow a desired robot trajectory with up to 47 degrees of freedom. If collision detection is desired, this trajectory can be generated by *The Kautham Project* (Rosell et al., 2014), a motion planning and simulation environment developed at the Institute of Industrial and Control Engineering (IOC-UPC) for teaching and research. Based on the information from the RGB-D camera mounted on the robot and the current robot state (base pose, the configuration of the arms and hands, and sensor measurements), *The Kautham Project*, asynchronously but continuously (re)computes the robot geometric path in order to safely navigate and solve a given task, using the new available information of the robot and of the environment, and tries to do human-like movements (García et al., 2017). Then, this multi-dimensional geometric path is transformed into a phase-synchronized trajectory (i.e. the given path is described as a function of time with all the joints accelerating and decelerating at the same time), using the library *Reflexxes* (Kröger, 2011) and considering the physical limits of the robot (i.e. maximum achievable joint velocities and accelerations). Finally, this trajectory is sent to the control layer and executed by the robot.

4. CONCLUSIONS AND FUTURE WORK

This paper has presented MADAR, an experimental general purpose mobile manipulator with original omnidirectional wheels. In particular, the design, installation and control of the new type of wheels has been described, as well as the control of the human-like torso that includes two arms with anthropomorphic hands equipped with tactile sensors. MADAR allows the test of new planning algorithms for mobile manipulation as well as to combine them with in-hand dexterous manipulation.

As future work, it is planned to study of the vibrations originated from the omni-directional wheels and its influence on the dexterous manipulation, which is a quite relevant topic that is not usually addressed by the manufactures of mobile manipulators. This problem is frequently avoided by moving the mobile platforms with extremely slow velocities or stopping them before doing manipulation tasks. Enhance the sensorial capabilities of the mobile manipulator and the performance of the synchronization and control libraries is also an open topic for future improvements.

REFERENCES

Adascalitei, F. and Doroftei, I. (2011). Practical applications for mobile robots based on mecanum wheels - a systematic survey. *Romanian Review Precision Mechanics, Optics and Mechatronics*, 21–29.

Albu-Schöffer, A., Haddadin, S., Ott, C., Stemmer, A., Wimböck, T., and Hirzinger, G. (2007). The DLR lightweight robot: Design and control concepts for robots in human environments. *Industrial Robot: An Int. J.*, 34(5), 376–385.

Barraquand, J. and Latombe, J.C. (1989). On nonholonomic mobile robots and optimal maneuvering. In *Proc. IEEE Int. Symp. Intelligent Control*, 340–347.

Batlle, J. and Barjau, A. (2009). Holonomy in mobile robots. *Robotics and Auton. Systems*, 57(4), 433 – 440.

Batlle, J., Font-Llagunes, J., and Barjau, A. (2010). Calibration for mobile robots with an invariant Jacobian. *Robotics and Auton. Systems*, 58, 10–15.

Bischoff, R., Huggenberger, U., and Prassler, E. (2011). KUKA youBot - A mobile manipulator for research and education. In *Proc. IEEE Int. Conf. Robotics and Automation*, 1–4.

Clos, D. and Martínez, J. (2015). Omnidirectional wheel, and omnidirectional mobile device. *World Intellectual Property Organization*, (Patent WO 2015/121521 A1, lens.org/084-354-767-767-633).

Dean-Leon, E., Pierce, B., Bergner, F., Mittendorfer, P., Ramirez-Amaro, K., Burger, W., and Cheng, G. (2017). TOMM: Tactile omnidirectional mobile manipulator. In *Proc. IEEE Int. Conf. Robotics and Autom.*, 2441–2447.

Ferriere, L. and Raucent, B. (1998). ROLLMOBS, a new universal wheel concept. In *Proc. IEEE Int. Conf. Robotics and Automation*, volume 3, 1877–1882.

García, N., Rosell, J., and Suárez, R. (2017). Motion planning by demonstration with human-likeness evaluation for dual-arm robots. *IEEE Trans. Systems, Man, and Cybernetics: Systems*, PP(99), 1–10. doi:10.1109/TSMC.2017.2756856.

Khatib, O. (1999). Mobile manipulation: The robotic assistant. *Robotics and Auton. Systems*, 26(2), 175 – 183.

Kröger, T. (2011). Opening the door to new sensor-based robot applications - The Reflexxes Motion Libraries. In *IEEE Int. Conf. Robotics and Automation*, 1–4.

Kurazume, R. and Hasegawa, T. (2006). A new index of serial-link manipulator performance combining dynamic manipulability and manipulating force ellipsoids. *IEEE Trans. Robotics*, 22(5), 1022–1028.

Montaño, A. and Suárez, R. (2015). Unknown object manipulation based on tactile information. In *IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, 5642–5647.

Montaño, A. and Suárez, R. (2018). Manipulation of unknown objects to improve the grasp quality using tactile information. *Sensors*, 18(5-1412).

Reitelshöfer, S., Ramer, C., Gräf, D., Matern, F., and Franke, J. (2014). Combining a collaborative robot and a lightweight Jamming-Gripper to realize an intuitively to use and flexible co-worker. In *Proc. IEEE/SICE Int. Symp. System Integration*, 1–5.

Rojas-de-Silva, A. and Suárez, R. (2016). Grasping bulky objects with two anthropomorphic hands. In *IEEE/RSJ Int. Conf. Intelligent Robots and Systems*, 877–884.

Rosell, J., Pérez, A., Aliakbar, A., Muhayyuddin, Palomo, L., and García, N. (2014). The Kautham Project: A teaching and research tool for robot motion planning. In *Proc. IEEE Int. Conf. Emerging Technologies and Factory Automation.*

Runge, G., Borchert, G., and Raatz, A. (2014). Design of a holonomic ball drive for mobile robots. In *Proc. IEEE/ASME Int. Conf. Mechatronic and Embedded Systems and Applications*, 1–6.