ALTER-EGO: a Mobile Robot with Functionally Anthropomorphic Upper Body Designed for Physical Interaction.

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I. Introduction

Historically, robots first found application in factories and plants. Until recently, the most noticeable examples of robot systems directly sold to the consumer were limited to edutainment systems (e.g. NAO [1]), automated chore robots[1], and social tele-presence platforms[2]. Initially, telepresence robots consisted in a mobile base bearing an interactive screen. Nowadays, following a trend of anthropomorphization of technology, human-like upper-bodies are starting to replace those simple screens (e.g. Pepper [2], R1 [3]) and sharing the same social communication modalities of humans, e.g. body posture, gestures, gaze direction and facial expressions. Unfortunately, social robots are mostly designed to speak and make gestures, while they have limited capabilities when it comes to physically interacting with people and with the surrounding environment.

On the other hand, looking at the state of art, there are promising examples (e.g. Walkman [4], Atlas [5], TORO [6]) of humanoid robots developed to operate in unstructured environments and perform challenging interaction tasks, e.g.: walking on rough terrains, moving heavy objects, solving complex bi-manual manipulation tasks. Specific enabling technologies led to the effectiveness of these robots letting them interact with the surrounding world, e.g. active impedance control in TORO, and series elastic actuation in Walk-Man. Indeed, these same technologies are among the enablers that let robot arms cross the borders of industrial work cells, to become collaborative robots that can work in close contact with people and share the same operating space. Although both humanoid robotics and teleoperation have a long history, the authors believe that three factors are concurring today to enable the diffusion of robots in real environments. The first factor is the success and diffusion of Soft Robotics. Technologies like series elastic actuation, variable impedance, and tele-impedance controllers, enable machines to interact safely and effectively with the humans and the environment. The second factor is the commoditization of hardware and software technologies that until recently were relegated to very specialized engineering fields, as nuclear, military and aerospace. Examples of these technologies include virtual reality headsets, integrated inertial navigation units, high-bandwidth and low-latency networking, and in general affordable computational power and reliable sensing. The third factor is the increasing interest by large companies and funding agencies, that are fostering novel humanoid robotics and teleoperation developments by opening competitions and awarding prizes. Two notorious examples are 2015's DARPA Robotics Challenge (DRC - 8M$ prize)[3] and the recent ANA - Avatar XPRIZE (XP - 10M$ prize) [4]: *"...a four-year global competition focused on accelerating the integration of several emerging and exponential technologies into a multipurpose avatar system that will enable us to see, hear, touch and interact with physical environments and other people through an integrated robotic device"*.[5]

Fig. 1. ALTER-EGO, a soft dual-arm mobile platform equipped with variable stiffness actuation units and soft under-actuated hands.

The focus of the latter includes the domains of healthcare, services, inspection, and maintenance, pointing out the importance of physical interaction capabilities, sensing integration, and user friendliness.

Inspired by these challenges and perspectives, and leveraging on our previous experiences and contributions [4], [7],

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[1] https://www.irobot.it/roomba
[2] http://www.fernarbeiter.de/en/
[3] https://www.darpa.mil/program
[4] https://avatar.xprize.org/prizes/avatar
[5] Extracted from ANA - Avatar XPRIZE Guidlines, March 12 2018.

	N	Task	Vision		Hear	Speak	T. S.	F. S.		Locom.		Manip.	P. Int.	Operation M.		
			1st P.	3rd P.				Arm	Grasp	Wheels	Legs			I. Tel.	Teleop.	Auto.
Scenario 1	X1	Greet your relative in an assisted living facility	✓			✓				✓				✓	✓	✓
	X2	Administer morning medications (pills and liquid)	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓		
	X3	Push a wheelchair five meters up a ramp to a room	✓	✓				✓		✓			✓	✓	✓	✓
	X4	Discuss available daily activities with staff	✓		✓	✓				✓				✓	✓	
	X5	Identify a board game such as chess or go in a box on a shelf. Pick it up, bring it to a table, and set it up for play	✓	✓			✓	✓	✓	✓		✓	✓	✓		
	X6	Listen an announcement of a visiting doctor for checkups	✓		✓									✓	✓	
	X7	Push your relative five meters to the doctor's station	✓	✓				✓		✓			✓	✓	✓	✓
	X8	Read the written checkup report aloud and sign it	✓			✓	✓	✓	✓	✓			✓	✓		
	X9	Push the relative back down the ramp to original spot	✓	✓				✓		✓			✓	✓	✓	✓
	X10	Take a blanket from wheelchair, fold it, put it on a shelf.	✓				✓			✓		✓		✓		
Scenario 2	X11	Use a shovel to load 20kg of debris into a wheelbarrow	✓	✓				✓		✓			✓	✓		
	X12	Push the wheelbarrow 10m to a loading area	✓				✓	✓		✓				✓	✓	✓
	X13	Use the shovel to unload the wheelbarrow	✓	✓				✓		✓			✓	✓	✓	✓
	X14	Return to original location and listen for a call for help		✓	✓					✓					✓	✓
	X15	Locate the source of the call for help	✓	✓	✓											✓
	X16	Walk forward to that location on a rough, dirt surface	✓	✓							✓		✓		✓	✓
	X17	Pick up a coiled rope with a weighted end	✓				✓			✓		✓		✓	✓	✓
	X18	Throw the weighted end of the rope towards the sound	✓	✓	✓					✓		✓				✓
	X19	Turn your head and call loudly for assistance	✓			✓								✓	✓	
	X20	Hand the unweighted end of the rope to an assistant	✓	✓				✓		✓		✓	✓	✓	✓	✓
Scenario 3	X21	Locate a set of instructions and read them aloud	✓			✓								✓	✓	
	X22	Pour specified quantity of fluid from a beaker to another	✓				✓	✓	✓	✓		✓	✓	✓		
	X23	Use a scoop to collect a specified sample of powder	✓				✓	✓		✓		✓		✓	✓	✓
	X24	Unroll a plan on a flat table, place weights on its corners	✓	✓			✓	✓		✓		✓	✓	✓		
	X25	Using a protractor, straightedge, and mechanical pencil, draw two lines on the plan that intersect at 45 degrees	✓				✓	✓	✓	✓		✓	✓	✓		
	X26	Identify broken plug-in components on an electrical panel	✓				✓	✓	✓	✓		✓		✓		✓
	X27	Walk 6 meters to a workbench and solder a wire on it	✓				✓	✓	✓	✓		✓		✓		✓
	X28	Return to the control panel and replace the component	✓				✓	✓	✓	✓		✓		✓		✓
		XPrize Total	**28**	**13**	**5**	**6**	**13**	**17**	**8**	**23**	**1**	**13**	**14**	**24**	**15**	**16**

TABLE I

TASKS AND SUB-TASKS OF THE XP[5] COMPETITION. **VISION**, FIRST AND/OR THIRD PERSON VIEW MODE; **HEAR**, HEARING CAPABILITIES; **SPEAK**, SPEAKING CAPABILITIES; **T. S.**, TOUCH SENSING MANAGE THE DELIVERY OF TOUCH FEEDBACK; **F. S.**, FORCE SENSING MANAGE THE FORCE FEEDBACK OF THE SYSTEM, OF *Arms* AND OF *Grasp*; **LOCOM**, LOCOMOTION CAN BE PERFORMED WITH *Wheels* OR *Legs*; **MANIP.**, MANIPULATION CAPABILITIES ARE REQUIRED, I.E. BI-MANUAL; **P.L INT.**, A PHYSICAL INTERACTION BETWEEN THE ROBOT ANT THE ENVIRONMENT/OBJECT/PEOPLE IS REQUIRED; **OPERATION M.**, IDENTIFY THE OPERATION MODE THAT BEST FIT THE GIVEN TASK, *I. Teleop.*, IMMERSIVE TELE-OPERATION (VIRTUAL REALITY HEADSET, PLUS MOTION CAPTURE SYSTEM), *Teleop.*, NOT IMMERSIVE TELE-OPERATION, AND *Auto.*, AUTONOMOUS MODE.

in this work we present ALTER-EGO. The robot, shown in Fig. 1, is a robust and versatile mobile system with a functional anthropomorphic upper-body. To perform safe physical human-robot interactions and to operate in different working scenarios, ALTER-EGO is powered by Variable Stiffness Actuators (VSA) that exhibit a stiffness behavior similar to that of human muscles [8]. Each arm mounts an anthropomorphic synergistic artificial hand inspired by the human motor synergies [7]. The upper body is mounted on a two-wheels self-balancing mobile base to minimize the robot footprint and increase agility. The system is equipped with sensors and computational systems that make the robot able to work autonomously. Moreover, ALTER-EGO can also be used in tele-operation from a pilot station mainly composed of lightweight and wearable interfaces. The system features an immersive control mode, which can use Tele-Impedance control [9] to match the pilot and robot mechanical behavior, not only in terms of movements, but also in terms of intended interactions behavior. The main contributions of this work are (i) the integration of a platform based on soft robotic technologies (VSA and tele-impedance) that can imitate the muscular behavior humans (Sec. III), and the description of its operating modes (Sec. IV) and pilot interface (Sec. V); (ii) the exploration of the use of a functionally anthropomorphic system for safe and effective physical interaction with people and the environment (Sec. VI). Finally (iii), most of the hardware and software technologies adopted, developed and explicitly designed for ALTER-EGO, are distributed under an open-source framework, and are available on the Natural Machine Motion Initiative website[6] (NMMI). To the best of the authors' knowledge, this is the first time that variable stiffness technology is built in an anthropomorphic platform with mobility capabilities and with different control modalities ranging from autonomous, to tele-operation.

[6]`www.naturalmachinemotioninitiative.com`

II. Requirements Analysis

The design requirements of a robot for application to general activities of daily living where a personal robot may be used, differs substantially from industrial or specialized machines. The tasks required by the XP competition, collected in Table I, can be used to distill a set of functional specifications[7] to motivate and guide the design of ALTER-EGO.

Manipulation: half the tasks require manipulation (13 on 28), and almost all physical interaction (14/28). Moreover, the simultaneous presence of tasks where (i) the robot has to push large and heavy objects, where (ii) finesse and precision are important, and where (iii) interaction force control is mandatory (e.g. because of safety), suggesting impedance control in the robot arms.

Locomotion: only 1 locomotion task out of 28 strictly requires the use of legs, making wheels a feasible although sub-optimal choice. Anyway, it is important to note requirements in terms of agility thus a small footprint.

Intelligence: The combined requirement of all the task in terms of intelligence acknowledge the unfeasibility of either a fully autonomous or fully tele-operated solution, favoring a shared autonomy approach. Indeed, while some tasks could benefit from immersive tele-operation, to enhance the pilot sense of presence, other could prefer console-based tele-operation to minimize fatigue, and, finally, other favor autonomous operation.

Sensing: vision is, straightforwardly, the most important sensory system, indeed it is required in almost all the tasks. Note, nevertheless, that the possibility to abstract from the subjective viewpoint (the "eyes" of the robot) to a third person view can benefit scene awareness of the operator in 13/28 tasks. Hearing (5/28) and Speaking (6/28) capabilities play a fundamental role in inspection and social interaction activities. All the tasks that involve physical interaction require touch sensing (13/28) or force sensing (17/28). In parallel, this raises also the issue of delivering touch and force feedback to the operator senses. It is out of the scope of this paper to discuss all these technologies in detail, please refer to [11] for a review, and to Sec. V for the description of the solutions integrated in the proposed system.

Pilot Interface: XP competition explicitly address also the fundamental aspects of usability and intuitiveness of control interfaces for non-trained users. These requirements should reflect on several aspects of the robot design, paving the way to another relevant consideration: the robotic system is not constituted solely by the robot itself, but to a much wider extent, by its combination and integration with the infrastructure that must be used to effectively operate it, i.e. the *pilot station*. This underlines the relevance of aspects as graphical user interface, and of the software capabilities, but also of the ergonomics of the input devices, of the time needed to set the system up, and of the overall weight of the wearable devices that the operator should use (especially in immersive tele-operated modalities).

[7]Although, it is out of the scope of this work to propose a deterministic approach to the definition of robot requirements and specifications, as well as to propose a robot that perfectly fits all these requirements.

III. ALTER-EGO

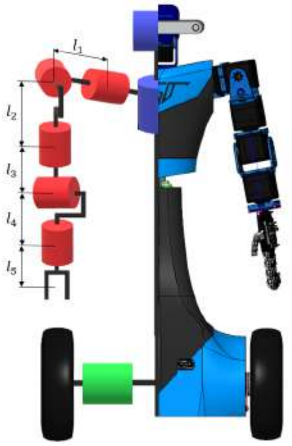
Fig. 2(a) shows some kinematic and mechatronic details of ALTER-EGO. The mobile platform has two independent wheels actuated by two DC motors. The upper body has five DoFs for each of the two arms, and integrates a robotic head mounted on a two DoFs neck, which allow the head to pan and tilt (see Fig.2(a) and (b)). The neck is mounted on the trunk. All the DoFs of the Upper Body are actuated by VSA units to enable safe physical interaction with environment and with people (even children, see the video footage). The presence of VSA units increases also the robustness of the system both in terms of control (as the soft behaviour mitigates passively external disturbances, e.g. from the balancing control), and mechanical failures (as e.g. during a fall). Moreover, the adoption of the same actuation units in all of the robot joints yields a simple modular architecture (e.g. all the joints are assembled with the same interconnection flanges), facilitating reconfiguration and parts substitution (e.g. in the event of a failure). Two soft anthropomorphic hands complete the robot.

The robot footprint clearance is 500 mm large and 260 mm deep, while the robot height is 1000 mm. The robot weighs about 21 Kg and its two-handed payload is 3 Kg, yielding a 0.143 weight to payload ratio. Its average speed is 0.25 m/s. The autonomy of the robot, in combined usage condition, ranges between 4 and 6 hours. The following subsections briefly describe the manipulation, locomotion and sensing subsystems composing ALTER-EGO. Note that: (i) all details about the building blocks forming ALTER-EGO and (ii) all the instruction on how to assemble, run and operate the system, can be downloaded from the NMMI website and github page[8] (see also [7]).

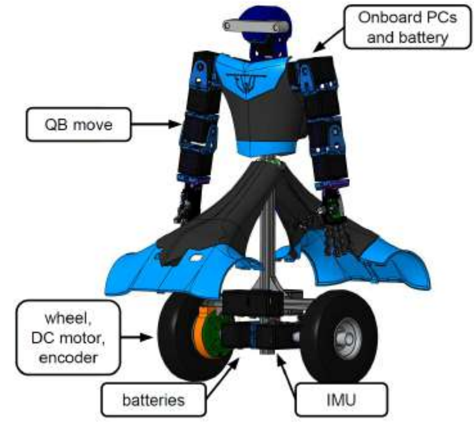
A. Locomotion

The robot Lower Body is composed of a rigid frame connecting the upper body to a two-wheeled mobile base, see Fig.2(a) and Fig.2(b). While most of the robots for structured scenarios have at least three-wheels to avoid stability problems, this choice often leads to the introduction of trade-offs between mobility and agility, e.g. leading to either the adoption of small wheels to save the footprint, disfavoring the capability of the system to deal with obstacles. For this reason, we choose to equip ALTER-EGO with only two wheels, similarly to what has been done in [12], and [13], to avoid such trade-offs. Each wheel has a diameter of 260 mm, is equipped with a low profile off-road tire, and is powered by a DC Maxon Motor (DCX22L, 12 Volt) in combination with a Harmonic Drive gearbox (160:1). The lower body of the robot (see Fig.2(b)) hosts a 9-axis IMU (MPU-9250 TDK InvenSense) between the two wheels, to estimate the pitch angle, and two magnetic encoders (AS5045 Austrian MicroSystems), to measure the rotation of the wheels. Moreover, two infrared GP2Y0A02YK0F sensors by Sharp are

[8]`https://github.com/NMMI/EGO`



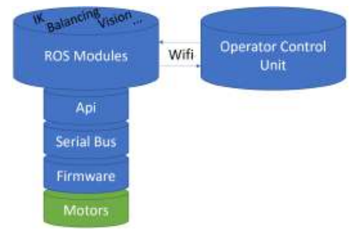
(a)



(b)

Right Arm				
Link	a_i	α_i	d_i	θ_i
1	ø	$\pi/2$	l_1	θ_1
2	ø	$-\pi/2$	ø	$\theta_2+\pi/2$
3	ø	$-\pi/2$	l_2+l_3	$\theta_3-\pi/2$
4	ø	$\pi/2$	ø	θ_4
5	ø	$-\pi/2$	l_4+l_5	θ_5

(c)



(d)

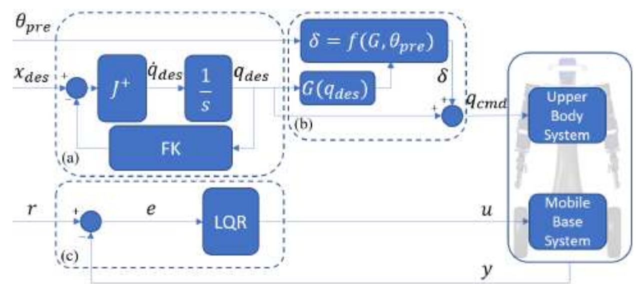
Fig. 2. (a) and (b) show the mechatronic architecture of ALTER-EGO. (c) and (d) show Denavit-Hartenberg parameters of arms, and the overall software architecture. l_i represents the length of i-th link, a_i, α_i, d_i, θ_i are the Denavit-Hartenberg parameters of the i-th link [10]

integrated in the base to prevent collision with low clearence obstacles.

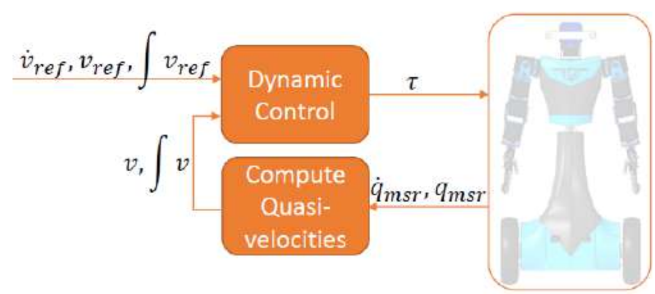
The independent control of the two wheels allows the system to move forward, move backwards and turn in place. Moreover, the possibility for the robot to adapt its pitch angle to the dynamical conditions, improves the execution of push/pull tasks, as well as the tackling of slopes (please refer to Sec.VI for more details).

It is worth to notice that this solution is not devoid of drawbacks, indeed, it introduces in the platform the need for an active balance stabilization, which could incur in instability issues, and may increase the energy consumption. Moreover, the balance control may also have consequences on the manipulation capabilities of the system. Indeed, changes in the center of mass of the robot, can affect the cartesian position and orientation of the head and end-effectors. These effects can have negative consequences (e.g. in a teleoperation setting, see also Sec. IV), and make manipulation more difficult unless a careful control ensures that the end-effectors are not affected by these oscillations, or the pilot actively manages such changes. Please refer to Sec. VI for more details on this regard.

In Se. III-C we describe the stabilization controls that we implemented in the robot, and in Sec. VI we show how the robot acts in case of accidental impacts and how is capable to stably interact with the environment as well. The complete solution of such kind of problems needs a deeper investigation, with the introduction of improved control algorithms, mechanical safety systems, or possibly both. In this regard, in ALTER-EGO it is possible to activate a whole-body balancing controller (as an alternative to the available and more conventional LQR control, see Sec. III-C) that takes advantage of the full system dynamics, including the arms, to improve the balancing performance (for more details refer to Sec. III-C and [14]).



(a)



(b)

Fig. 3. ALTER-EGO Control Schema. The full state feedback control system obtained with LQR is reported in (a). The Whole-Body control schema is showed in (b).

B. Manipulation

A revised release of the Pisa/IIT SoftHand [7], SH, was specifically designed for ALTER-EGO, in order to match the robot payload and dimensions (weight: 0.290 Kg; length; 130 mm). The SH is a heavily under-actuated anthropomorphic hand (19 degrees of freedom actuated by a single motor) capable to self adapt its grasp to objects of different shape, size, and weight, and to safely and effectively interact with people and the environment.

The main actuators of ALTER-EGO's arms and neck are 12 qbmove units. These are modular VSAs derives from the design of the VSA-CUBE [7], that implement an agonisticantagonistic principle by using two motors connected to the output shaft through a non linear elastic transmission. Each module is able to mechanically change its output shaft position and mechanically set a given output shaft stiffness profile.

The anthropomorphic structure of the upper body is obtained by connecting each of the two arms to a frame, which is, in turn, mounted on the mobile base, see Fig.2(a) and Fig.2(b). Each arm presents a relative angle w.r.t. the frame in order to maximize the common manipulation workspace, a solution that is commonly used in other bi-manual systems (e.g. [4]). Each arm has 5 DoFs, for this reason the robot may incur in unreachable configurations and singularities, especially when tele-operated. Such kinematics is the results of a trade-off between weight, complexity, length of the arm and actuators maximum payload.[9] Given the desired end-effector pose (position and orientation), the desired joint positions of each arm are computed via Closed-Loop Inverse Kinematics (CLIK) algorithm, with damped pseudo-inverse [10]. The orientation of the pilot's head is mapped directly to the corresponding Euler angles (pitch and yaw) of the robot neck (Fig. $3(a)$). For each *qbmove* of the upper body a position/stiffness control is used. Given the elastic nature of VSA, to control the position of the robot arms in feed-forward without steady-state error, it is necessary to compute both the desired actuator position and the expected load torque τ, in order to be able to compensate the expected elastic deflection δ. The vector τ can be easily extracted by the robot dynamics as

$$\tau = B(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) - J^T f_e \,, \tag{1}$$

while the expected deflection can be reconstructed by inverting the elastic model of the *qbmove*

$$\tau = k_1 \sinh\left(a_1(q-\theta_1)\right) + k_2 \sinh\left(a_2(q-\theta_2)\right) \,, \tag{2}$$

where (k_1, k_2, a_1, a_2) represent model parameters reported in the data-sheet available on NMMI, q is the link position and (θ_1, θ_2) are the positions of the two motors. Since $k_1 \simeq k_2 = k$ and $a_1 \simeq a_2 = a$, it is possible to write τ as

$$\tau = 2k\cosh\left(a\theta_{pre}\right)\sinh\left(a(q-\theta_{eq})\right) \tag{3}$$

where:

$$\delta = q - \theta_{eq} \,, \theta_{pre} = (\theta_1 - \theta_2)/2 \,, \theta_{eq} = (\theta_1 + \theta_2)/2 \,, \tag{4}$$

are the deflection, stiffness regulation and equilibrium angles respectively. Given a desired θ_{pre} and q, it is possible to reconstruct from 3 the expected deflection $\delta = \delta(q, \theta_{pre})$, thus the desired motor trajectory is $\theta_{eq} = q + \delta(q, \theta_{pre})$. Fig. $3(b)$ reports the adopted compensation scheme, where for simplicity $\tau \approx G(q)$.

[9]Different shoulder configurations, more anthropomorphic and with increased payload capabilities, are currently under investigation, e.g. refer to [17] for more details).

C. Control

In a simplified model, the state-space of the lower body sub-system has three generalized coordinates (θ, ψ, ϕ) which describe the semi-sum of the wheel angles, and the robot yaw and tilt angles respectively. Fig. $3(a)$ shows the balance control scheme, with $u = [u_1 \;\; u_2]$ representing the torque control for the two wheels, and $e = r - y$ is the error between the current y and desired r robot states. The desired state can also be modified by the operator using the available tele-operation devices (see Sec. IV). A classical LQR method can be applied to stabilize the wheeled base (as in in [15] and [16]), which can be simply designed but does not take advantage of fast balancing motions of the arms. This method is suitable when arms are not available to balance (e.g. because they are used in other tasks), and provides good balancing performance, as shown in Sec. VI

To improve over the performance of the independent LQR control in [14] we developed a new whole-body dynamic control system that computes the joint actuation torques τ given a desired joint space motion to track. To achieve this, a computed torque control law in the quasi-velocity vector is developed starting from the underactuated and kinematically constrained model of ALTER-EGO. Notice that the model considered in [14] does not take into account the variable stiffness of the robot upper body explicitly, an open subject of research. The idea of [14] follows in brief. Let q be the generalized coordinates of the robot, n the number of degrees of freedom, n_{fb} the number of independent variables needed to describe the floating base motion, and n_c the number of constraints acting on the robot, for instance due to the base kinematics. Then let $\nu \in \mathbb{R}^{n+n_{fb}-n_c}$ be the quasi-velocity vector, so that $\dot{q} = S(q)\nu$. Consider the error dynamics

$$\dot{\nu}^d - \dot{\nu} + K_d(\nu^d - \nu) + K_p \int_0^t (\nu^d - \nu) = 0, \tag{5}$$

where K_p, K_d are positive definite gain matrices and ν^d are the desired quasi-velocities. The resulting generalized torques are computed as a function of the quasi-velocities vector, as

$$\tilde{\tau} = \tilde{M}\left(\dot{\nu}^d + K_d(\nu^d - \nu) + K_p \int_0^t (\nu^d - \nu)\right) + \tilde{c}, \tag{6}$$

where $\tilde{c} = S^T(q)\left(M(q)\dot{S}(q,\dot{q})\nu + C(q,\dot{q})S(q)\nu + G(q)\right)$ and $\tilde{M} = S^T(q)\,M(q)S(q)$. This ensures that the resulting generalized torques are compatible with the constraints by design. We show in [14] that the actual joint torques τ can be obtained from 6 to obtain a whole-body control method. The method was tested in several experiments to stabilize the robot around an equilibrium position in presence of static and dynamic disturbances (see Fig.s 6(c) and 6(d)), as well as in tracking some desired motions during the execution of a task with physical interaction with the environment.

D. Sensing

The head is equipped with a Stereolabs Zed Camera[10]. This is a passive RGB-D depth camera that can acquire

[10]`https://www.stereolabs.com/`

(a) Input and output Devices

(b) Pilot Station for autonomous and tele-operation mode

(c) Pilot Station for immersive tele-operation mode

Fig. 4. (*a*), ALTER-EGO's input and output interfaces. (*b*) and (*c*), autonomous and immersive tele-operation pilot station configurations.

images, videos, and a depth point cloud of the scene. Images can be streamed to either the pilot station monitor, or to the Virtual Reality Headset when the robot is used in teleoperation mode (see Sec.V). ALTER-EGO is equipped with a set of basic vision tools that make it capable to recognise objects and markers. A wrapper is available in order to make the Zed stereo Camera usable in the ROS environment, providing access to stereo images, depth map, 3D point cloud and 6-DOF tracking. Several software systems exist that exploit state-of-the-art object detection algorithms. For this purpose Detectron[11] has been used on ALTER-EGO. The head architecture is completed by a 10 W speaker and a multi-directional 6-channels microphone.

Each of the two hands is equipped with position and current sensors on its motor, to reconstruct the applied grasp force. Moreover, the fingertips of the hand can be conveniently equipped with IMUs in order to allow estimation of contact events and surface roughness, as described in [18].

Each actuation module is equipped with three position sensors (on the two prime movers, and on the output shaft), so to be able to measure the spring deflection. This measurement can be used to estimate the torque applied by each motor, and in turn to estimate the external wrenches applied to the end-effectors, using the Least-Square Approach explained in [19].

E. Mechatronics, Software and Communication Architecture

ALTER-EGO is equipped with a computational unit (NUC i5 compact computer), for the managing of control architecture, vision streaming and compression algorithms. The low level communication layer between actuation units, wheels, sensors and end-effectors is based on a RS485 protocol (2 Mbit/s).

The robot is equipped with two 24 V batteries, with a total capacity of 48000 mAh and a peak current of 100A. A dedicated battery (12 Volts, 30000 mAh) is used to supply the computational units.

The ALTER-EGO software architecture is organised into four layers Fig. 2(d). A first layer is constituted by the firmware running in each board used to control the joints, end-effectors, motor wheels and sensors. A second layer, also embedded in the electronic boards, manages the communication bus among the different devices constituting the robot hardware. A third software layer (API) supports the communication between the second layer and the ROS modules. Each ROS module manages the nodes used for: base motion, balancing, arms inverse kinematics, feed-forward gravity compensation, end-effector wrench estimation, localization, mapping, navigation and vision. Finally, a fourth layer is used to communicate with the pilot station, and manages the robot both in autonomous and in tele-operated modes.

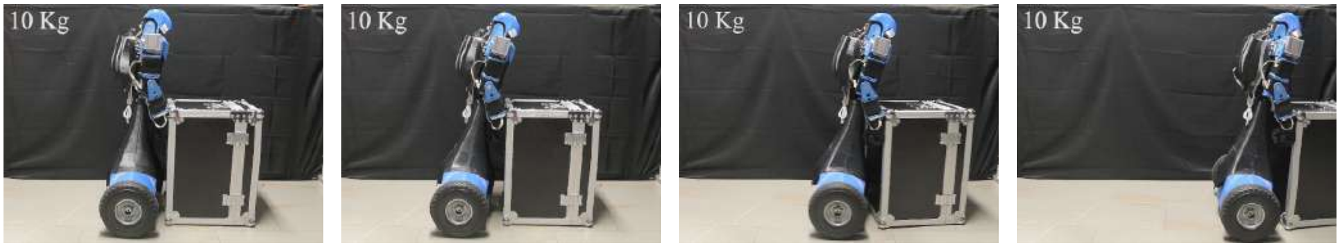
A dedicated communication framework allows to exchange data between the robot and the pilot station. A 5GHz wireless connection allows the bilateral communication with the pilot station for the streaming of control (e.g. sensors measurements, references positions), and vision data. A ROS communication framework is used to send commands to the robot and to receive data from it. A dedicated UDP connection has been developed to allow video data exchange between the robot and the pilot station (see Sec. IV). The pilot station sends the robot, at a frequency of 100 Hz, references of: head orientation, arm joint position and stiffness, hands closure and velocity vector for the mobile base. The robot sends back a stream of images at a frequency of almost 25 Hz, limited by capturing and processing delays. The measured average ping time between the pilot station and the robot is 15 ms, while the average bandwidth used for both motion commands and image streaming was measured: respectively a bandwidth 1 MB/s and 18 MB/s were used. Internet infrastructures was used in some experiments to connect the pilot station to the robot operation site, where it is completed by 5GHz wi-fi (see video footage).

IV. Operating Modes

The ALTER-EGO have two main operation modalities.

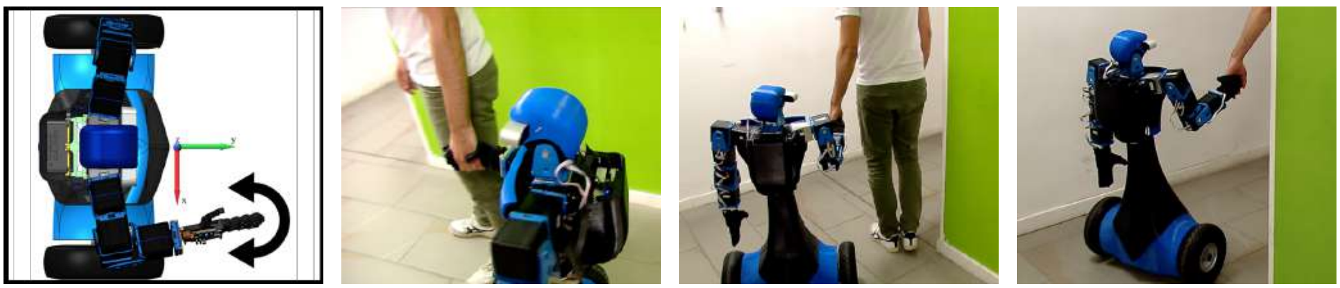
Autonomous mode: In this operating mode ALTER-EGO can be used in a complete autonomous fashion, leveraging on some core functionalities embedded in its local computational unit. For the purpose of autonomous navigation Simultaneous Localization and Mapping (SLAM) algorithms are used. More specifically, a RGB-D Graph SLAM approach based on a global Bayesian loop closure detector is used,

[11]https://github.com/facebookresearch/detectron



(a) ALTER-EGO pushing a heavy box (10kg).

(b) ALTER-EGO carrying an heavy box in collaboration mode with a human.



(c) ALTER-EGO following a human operator.

Fig. 5. Autonomous actions: pushing an heavy object (a), carrying a box in collaborative mode (b), and following a human operator (c).

RTAB-MAP [20]. Although the use of RTAB-MAP allows to localize ALTER-EGO accurately, occlusion camera and slow update rate (10 hz) impede robot localization in some cases. To solve this problem a particle filter [21] is integrated in the system. By the end the velocity of wheels (measured by encoders) and visual odometry (obtained by RTAB-MAP) are used, respectively, for prediction and correction phases. Particle filter is used to know the current robot position and orientation. The combination of this information are used as feedback for waypoint-based navigation. For this purpose Pure Pursuit method [22] has been implemented on ALTER-EGO. ALTER-EGO is also equipped with some autonomous grasping and manipulation capabilities, which make it capable to grasp objects with two hands, using both vision and end-effector wrench estimation. Aruco[12] ROS package has been used in order to know object's position.

ALTER-EGO embeds an autonomous modality which allows the execution of collaborative tasks together with humans. In this operational mode ALTER-EGO is able to execute cooperative manipulation tasks, as e.g. handling an object in cooperation with humans, or walking hand in hand. In order to execute these kind of tasks end-effector wrench estimation has been used. In particular, (see Fig. 5 (b) (c)) the force in y direction and the torque around z direction are used as desired linear and angular velocity respectively in order to follow the direction imposed by the human.

Teleoperation mode: ALTER-EGO can be tele-operated from a consolle or trough an immersive virtual reality setup. In the latter case a motion capture system is needed to map pilot body movements to the robot kinemtatics. A key feature of the proposed tele–operation framework is its lightweight, reduced encumbrance and ease of wearing. In the standard setup two Myo-Aambands per arm (one placed on the forearm and one on the upper–arm) plus an additional IMU placed on the pilot's hand allow to reconstruct the cartesian position and orientation of the pilot limbs. Let ${}^{i}T_j \in R^{4\times 4}$ be the homogenous transformation from joint i to joint j, the homogenous transformation ${}^{S}T_H$ from the shoulder to the hand is given as follow:

$$ {}^{S}T_H = {}^{S}T_E \; {}^{E}T_W \; {}^{W}T_H \tag{7} $$

Where subscripts S, E, W and H indicate shoulder, elbow, wrist and hand, respectively. The translation part of every homogenous transformation is known a priori (length of the arm, forearm and distance between wrist and palm), whereas it is possible to compute ${}^{i}R_j \in R^{3\times 3}$ (rotation part of the homogenous transformation ${}^{i}T_j$) applying a Madgwick filter [23] on the data coming from the IMU placed on the arm and on the hand. The result of (7) is properly scaled in order to match with the length of the robot arms, and

[12] http://wiki.ros.org/aruco

then used as a cartesian reference for the inverse kinematics algorithm. This setup allow also the possibility to control the stiffness of the robot arms using the electromyographic data given by the MyoArmbands placed on pilot upper-arm, implementing a tele-impedance control as done in [4]. Hand closure is controlled by a linear combination of electromyographic signals from the MyoArmbands placed on the pilot's forearms, as reported in [7]. In this configuration a Wii Balance Board[13] is used to control the robot mobile base sending velocity references. More specifically, operator can move his own COM in order to move robot forward/back and turn left/right. This configuration is preferable when haptic feedback devices must be used, mainly because it leaves free the operator hands. In some circumstances a simplified version of the capture system can be used, simply relying on the sensors provided by the Virtual Reality system adopted (e.g. the Oculus Rift).

V. Pilot Interface

ALTER-EGO has a modular pilot interface that can be shaped accordingly with the different purpose of use, and with the different operation modalities. Key elements are Input, Visual, and Haptic Feedback interfaces. All these elements can be selected and switched during a session of use. A description of each subsystem of the pilot interface is reported in the following.

Computational and Communication Consolle: the ALTER-EGO pilot station, is composed by one laptop, used to manage, monitor and command the robot together with the different interfaces. The same laptop is used to handle the vision workload, in order to manage 3D and 2D visualisation, manage the virtual reality framework and vision algorithms. The pilot console is also equipped with a dedicated wireless router.

Visual Interfaces: ALTER-EGO has two main visual interfaces: standard screen visualization and immersive 1^{st} person virtual reality visualization. In the first option it is possible to visualize all the robot parameters on a screen, together with the visual streaming coming from RGB cameras. Moreover, using the support of ROS 3D visualizers (see Sec. III), it is possible to have a 3D reconstruction of the environment together with the 3D pose reconstruction of the robot. As a second option ALTER-EGO integrate also the possibility to use a virtual reality headset, such as the Oculus Rift ones. In this configuration an immersive visual representation of the world is possible.

Input Interfaces: several input devices can be used in order to acquire or compute references for the robot, both for the locomotion and manipulation subsystems. Common Joystick/Joypad, Keyboards and Mouses can be used to move the robot mobile base and the robot arms, buttons can be used to activate hands or starts predefined functions (see Sec.IIIIV). Currently a balance board (WII, specs) is adopted to control the forward/backward and turning movements of the mobile base. Wearable devices as the MYO ArmBand (9-axis IMU, plus 8-channels surface electromyography sensors, sEMG) are used to control the activation of the robot hands, manage the impedance of the actuation units and perform motion capture of the pilot movements in teleoperation mode (see Sec.IV). If a virtual reality headset is present, its motion capture system can be used to control the robot movements.

Haptic Feedback Interfaces: ALTER-EGO pilot station is conceived in order to allow to the pilot the use of different haptic feedback devices for the delivery of different haptic stimuli, which can be conveyed on the hands of the pilot or on others parts of its body (e.g. arms). To avoid typical issues related to instability given by the adoption of closed loop controls, ALTER-EGO adopts not-collocated feedback systems. Moreover, in most of the cases, a modality matching approach is followed (for more information please refer to [11]). Examples of feedback stimuli, developed under the same NMMI framework, which can be adopted in the platform are: hand grasp force [24], impacts and surface roughness [18], hand proprioception [25].

VI. Experimetns and Discussion

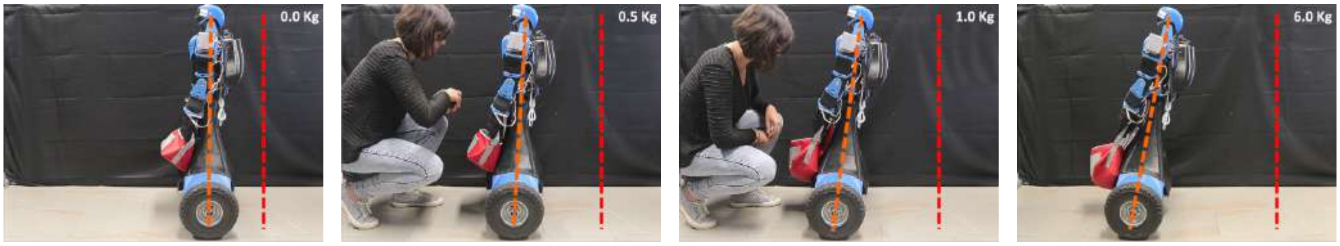
This Section reports experimental examples in order to demonstrate the effectiveness of the basic capabilities of the system, and to report some application example where ALTER-EGO is used in physically simulated and realistic contexts. Pictures and photo-sequences shown in this Section are extracted from the video footage linked to this manuscript. Fig.6 shows the balancing capabilities of ALTER-EGO. Fig.6(a) shows the robot dealing with different slope angles of the floor, by simply adapting the reference position of its COM autonomously. Fig.6(c) and 6(d) show the balancing behaviour in presence of dynamic disturbances. The former with the standard LQR control is used and the latter with the whole body control. It is possible to see how in the latter the balancing action involves also the movement of the arms. Fig. 6(b) shows the balancing behavior of the robot during the disturbance action of increasing static loads. Another advantage of the capability to autonomously change the COM of the robot is shown in Fig.5(a), where ALTER-EGO is moving a box (10 kg) simply pushing it, and autonomously reach the needed force adapting its pushing angle.

Examples of Human-Robot cooperation are reported in Fig 5(b) and 5(c), in these tasks ALTER-EGO has to cooperate with a human in order to carry a heavy box (10 kg), or following the human operator holding him by the hand. It is worth to note how, in these last three example of use, the soft nature of the robot upper–body avoids end–effector wrench transmission which would be a disturb for the balancing.

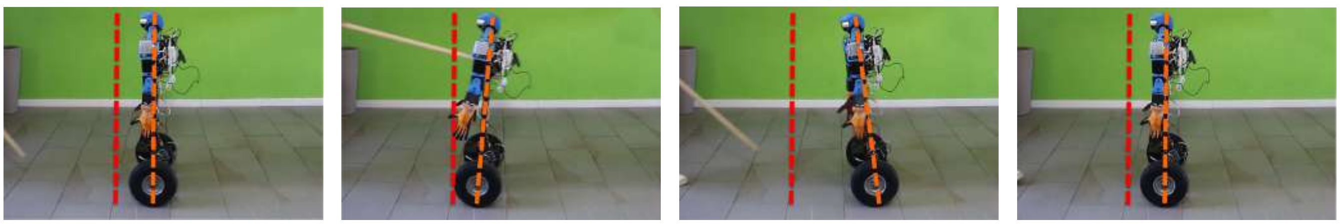
Fig. 7 reports examples of use of the robot in the execution of different tasks, and in different contexts. In Fig.7(a) ALTER-EGO is used in Immersive Teleoperation Modality and is possible to see how the robot was capable to open a door, grasp an object and provide it to a third user. From the picture it is possible to see both the movements of the robot and the movements of the human operator. Fig.7(b) shows

[13]https://www.nintendo.it/Wii/Wii-94559.html

(a) Robot balancing at different slope angles.



(b) Robot Balancing in presence of static disturbances.



(c) LQR control algorithm. Robot Balancing in presence of external impulsive disturbances.

(d) Whole-body control algorithm. Robot Balancing in presence of dynamic disturbances.

Fig. 6. (a) and (b) show the balancing behavior of the robot in presence of changes in the slope angle of the floor and static disturbances. (c) and (d) show the balancing performance (in presence of dynamic disturbances) with the LQR and the whole body controllers developed.

ALTER-EGO interacting with children during an exposition (MakerFair, Rome, 2017).

Fig.8 shows ALTER-EGO operating in a domestic use-case scenario (see video footage). Action showed are mostly executed with the immersive tele-operation operating mode, envisioning that an hypothetic user can jump inside the robot from its work location and teleport himself at home to assolve some domestic tasks. In Fig.8(a) and 8(b), the pilot use the robot to prepare food for a pet and to retrieve the box from the mail man, pay, and come back to the house. In Fig.8(c), the pilot simulate to assist remotely a relative thanks to the use of ALTER-EGO. In such case ALTER-EGO was able to provide a thermometer and pills to the relative, check the temperature, provide a blanket, check the cardiac frequency and provide food. The experimental activity was performed from two different locations posed at a distance of five kilometers (pilot station placed at the Engineering building of the University of Pisa), the tele-communication framework used an Internet connection with a bandwidth of 48 Mbit/s and 80 Mbit/s in download and 48.3 Mbit/s and 18 Mbit/s in upload, for the Pilot Station and domestic environment respectively. The ping was of 17 ms. Although not exhaustive such experience demonstrate the potential and effectiveness of the approach. Finally, Fig. 8(d) shows ALTER-EGO moving on a outdoor uneven terrain characterized by the presence of small rocks, grass roots and a slight descent.

The authors would like to point out and discuss also some drawbacks experienced while using the proposed platform. The advantages of using an agile two-wheeled-mobile base can be counterbalanced by the instability of the platform. Indeed, this can have critical, or even catastrophic, effects, for instance in the case of impacts with the environment during a manipulation task. The variation of center of mass (e.g.: movements of the arms or variation of payload) is used to update the feedforward action (desired pitch angle) to stabilize the robot. In the LQR control approach the perturbation on the desired pose of the end-effector (due

(a) ALTER-EGO opens a door, grasps an object, and interacts with people.

(b) ALTER-EGO physically interacts with children.

Fig. 7. (*c*) physical interaction with the environment in tele-operated mode. (*b*) physical interaction with children (MakerFair, Rome, 2017).

to the stabilizing controller) can be only corrected and compensated by the pilot, closing the external control loop through the vision feedback provided by the virtual reality headset. This approach is a rather simplistic solution to the problem, as we acknowledge, and better solutions could certainly be devised. Nevertheless, in the videos the pilot is able to accomplish the tasks notwithstanding the disturbances. In our experience, such phenomena are pretty well addressed when the robot is tele-operated in an immersive mode, because the pilot-robot interaction is rather intuitive, and the pilot has a direct idea of what is happening in the scene. Although we only have episodic data, one could venture to say that human pilots exploit their own instinctive ability to compensate for stabilization and manipulation interactions. For this reason we also introduced the whole-body balancing control method described in Sec. III-C. With this controller balancing performance improves, anyway a more in depth investigation is needed to better evaluate its performance during manipulation tasks. It is worth to be notice that other possible approaches to autonomous decoupling of manipulation and stabilization include the introduction of active counterbalance mass, as seen e.g. in recent Boston Dynamics[14] footage. Anyway such solutions do not fit well with the size and purpose of the ALTER-EGO platform, where the introduction of heavy counterweights could introduce safety concerns.

Some considerations can be also made on the current design of the neck-head subsystem. The current solution does not ensure to follow the trajectory of the pilot's head perfectly (please refer to Sec. IV). Nevertheless, at the moment, this choice does not prevent the pilot to operate the robot in a satisfactory way, as shown in the video footage. It is in the opinion of the authors that a solution with a more anthropomorphic design in the kinematic structure (i.e. at least three DoFs configured as a spherical joint, [17]) could allow for a better performance both in terms of vision capabilities and user experience (i.e. by reducing the typical motion-sickness that can occur after an intense use of a virtual reality system).

[14]www.bostondynamics.com/handle

VII. Conclusions

In this work we presented ALTER-EGO, a dual-arms mobile platform developed whit soft robotic technologies both for the actuation and manipulation layer. Features resulting from this kind of technologies, like flexibility, adaptivity and robustness allow ALTER-EGO to interact with environment and objects, as well as allow to improve safety when the robot is in action around humans. An overview of ALTER-EGO mechatronic design, pilot interface, core and high level functions was presented in this paper. Moreover, most of the hardware and software technologies adopted, developed and explicitly designed for ALTER-EGO, are distributed under an open-source framework, and are available on the Natural Machine Motion Initiative website (NMMI). The platform validation was performed in both inside and outside the lab and involved several tasks. In particular, the house simulated scenario showed the potential of such kind of use in real scenario. Future work will be devoted to the investigation of the role of haptic feedback interfaces, and to an extensive use of the platform in different fields.

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(a) (b) (c) (d)

Fig. 8. (a) and (b), the robot is tele-operated to prepare food for pets and to retrieve a box from a mail man. (c), a pilot's relative is assisted by ALTER-EGO. (e), the robot is operated in an outdoor terrain characterized by the presence of small rocks, grass roots and a slight descent.

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