A parallel kinematic mechanism for the torso of a humanoid robot: design, construction and validation

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Abstract— **The torso of a humanoid robot is a fundamental part of its kinematic structure because it defines the reachable workspace, supports the entire upper-body and can be used to control the position of the center of mass. The majority of the torso joints are designed exploiting serial or differential mechanisms, while parallel kinematic structures are less used mainly because of their greater design complexity.**

This paper describes the design and construction of a 4 degrees of freedom (DoF) torso for our new humanoid robot. Three degrees of freedom, namely roll, pitch and heave, have been implemented using a 3 DoF parallel kinematic structure, while the fourth DoF, namely yaw, has been implemented with a rotational joint on top of the parallel structure. The design has been optimized to reduce the cost and the volume of the system.

A first prototype of the torso has been constructed and validated with respect to our design requirements. Eventually, experimental tests have been conducted to assess the functionality of the proposed system.

I. Introduction

In the past decades, industrial robotics has been the dominating sector in the robotic sales worldwide. However, there are indications that today's robotics market is about to undergo substantial changes. Recent promising advances have been achieved in the emerging sector of service robotics mostly from research laboratories and universities. Service robots are intended to provide assistance and support in human-centric environments. Possible applications are customer care, elder care, housekeeping; more applications will probably be conceived as the sector grows. According to recent market analysis, service robotics has been accorded special attention because of its importance and future potential.

In the wake of this new technology, we recently focused on the development of a new robot. After almost one year and a half, we presented the first prototype of our new humanoid "R1"[1]. This new robot has a total of 28 Degrees of Freedom (DoF) and is statically stable on its wheeled mobile base. In particular, R1 features two 8-DoF arms with embedded 6 axis force/torque sensors, two 2-DoF hands with Series Elastic Actuator (SEA), a sensorized head supported by a 2-DoF neck and a 4-DoF torso, depicted in Figure 1. The torso design, in particular, has been thoroughly investigated because of its role in defining the reachable workspace, supporting the heavy load of the entire upper-body and controlling the position of the Center of Mass (CoM) to balance the robot.

Fig. 1: The figure shows a photograph of the prototype of the torso joint of R1. The system is directly assembled on the mobile base, while the robot chest is connected to the aluminum platform on top of the plastic plastic gear.

Different torso designs can be found in the literature, ranging from serial mechanisms to parallel and differential structures[2].

Serial kinematic torsos are usually easier to design and control because a single motor is used to actuate a single DoF. The major drawback is represented by the size of the motors which have to be big and heavy to provide the required joint torque. This inconvenience sometimes limits the number of the torso DoF to 2. As an example, the robots LOLA [1] and HRP-4 [2] employ two electric motors with harmonic drives to actuate pitch and yaw independently.

Parallel and differential torsos have in common the advantage given by their intrinsic synergistic behavior, indeed the joint torque is split among two or more actuators allowing

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[1]We are currently working on a general paper about our new robot, for an overview of R1 refer to https://www.youtube.com/watch?v=TBphNGW6m4o

[2]Differential joints can be thought as serial joint exploiting a parallel actuation arrangement.

for the use of smaller motors, reducing cost, volume and weight. However, all these features come at the cost of a greater complexity in design and control. As an example, the waist of the robot iCub [3] exploits a differential mechanism designed using steel cables. The robot ARMAR V [4], adopts a particular frameless differential design without bearings. Therefore the weight and dimensions of the unit have been further reduced.

Parallel Kinematic Manipulators (PKM) generally have good stiffness and accuracy if compared to their serial counterparts [5]. The major drawbacks that limit their application in humanoid torso joints are represented by the limited workspace and the occurrence of singularities. Nevertheless, some interesting application can be found in the literature. The robot Valkyrie [6] exploits a parallel actuation architecture to control the chest. In particular, the robot's 3-DoF waist consists of a pair of parallel linear SEAs providing pitch and roll on top of a rotary SEA providing yaw. The Laboratory of Robotics and Mechatronics (LARM) in Cassino has also proposed the conceptual design of two humanoid robots that exploit different PKM to actuate the torso joint [7]. CALUMA is a low-cost humanoid robot that exploits a 3-DoF PKM for its torso joint, while more recently an improved humanoid design has been proposed with a waist-trunk system consisting of two classical parallel structures connected together in a serial chain. The torso of the iStruct robot ape [8], developed to walk and climb like an ape over rocky ground, has been actuated by a 6-DoF octahedral hexapod platform.

Besides the torso joints based on common robotic structures considered so far, a few humanoid robots that try to replicate the complex structure of the human spine have also been designed. Interestingly, robots like Kenta, Kotaro, Kenzoh and Kenshiro [9] exploit a design based on vertebrae connected with spherical joints, where tension springs and rubber cushions are added to help to stabilize the spine. Eventually, the spine is actuated by tendons (wires) generating torques between the vertebrae.

During the development of R1 we had a different list of requirements motivated mainly by the goal of reducing the final cost of the entire robot and being able to manipulate objects at different heights. For this purpose we adopted a novel solution based on a parallel kinematic mechanism with 3 linear actuators.

The paper is structured as follows. Section II presents the design of the torso joint focusing on the requirements list, the selection of the conceptual design and the mechanical analysis of the proposed solution. Section III outlines the design evaluation together with the first torso prototype and the experimental tests. We conclude the paper describing the lesson learned and the next steps.

II. Design

The development of the novel torso joint has been tackled dividing the design process into four distinct phases. The first phase is represented by the description of the task and the definition of the design specifications. During this phase, we analyzed the constraints and derived a clear list of concrete and measurable requirements. The second phase is represented by the conceptual design. This phase is the most creative process and involves the conceptualization of the solution to the technical problem. The third phase is represented by the embodiment design and involves the definition of the layout and the form of the system in accordance with the technical and economical criteria. A fourth phase, represented by the detailed design, has been carried out but is not described.

A. Design requirements

As mentioned in the introduction, the design of the novel mechanism for the torso joint has been influenced mainly by the constraints on its final cost and to allow the robot to manipulate easily on a table 0.7 [m] high as well as to grasp objects from the floor. Further requirements have also been defined, like for example: improving the robot stability, fit all the mechanical components inside of the volume given by the style team and lower the robot weight to an acceptable value. In particular, we defined the following requirements list (ordered from most to least important):

1) **reduce the cost**: the final price of R1 is set to 12.000 € per unit for a production of 2000 units. The maximum budget allocated for the torso is 1500 €.
2) **achieve an acceptable range of motion**: the torso is only one part of the kinematic chain that connects the robot base to the hand. During the design of R1 we heavily relied on simulations to optimize the torso and arm kinematic parameters to fulfill the high-level requirement on the workspace. The final RoM for the torso joint was set to 0.2 [m] in extension, ± 30 [deg] in inclination for both pitch and roll and ± 60 [deg] for the yaw joint.
3) **minimize the volume**: all the mechanical components shall fit inside of the covering surfaces provided by the style team.
4) **lower the Center of Gravity (CoG)**: the robot has no legs and is supported by a wheeled mobile base. Lowering the robot CoG improves its static stability. The torso CoG shall be located in the lower half of the torso assembly.
5) **preserve an acceptable weight**: the target weight for R1 is 50 [kg] to ease its transportation by 2 people. For the torso 10 [kg] are allocated[3].

Additional requisites that have been considered include:

6) **increase stiffness**: when the upper-body is tilted the elasticities of the torso joint can greatly influence the accuracy in hand positioning, therefore a stiff structure is requested.
7) **minimize inertial loads**: reducing the inertial loads decreases the required joint torques.

[3]It is important to notice that this weight includes also the frame that connects the mobile base to the torso joint.

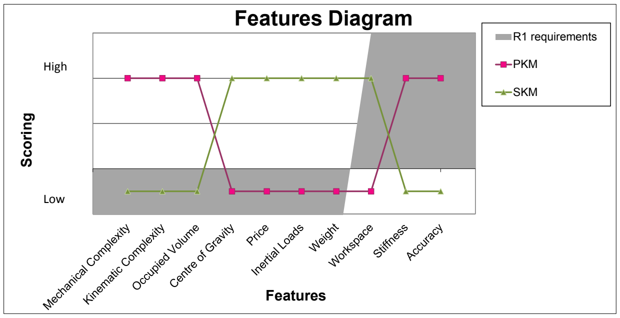

Fig. 2: The diagram compares the serial and parallel manipulators against our design requirements. The features are ordered from left to right to simplify the visualization of the curves minimizing the crossings.

B. Conceptual design

The conceptual design objective was to conceive a system optimized for our kinematic and cost requirements. Before selecting the design approach, we compared the serial and parallel structures to better understand their respective strengths and weaknesses. In particular, compared to serial counterparts, parallel manipulators have the following advantages [5], [10], [11]:

- the actuators can be placed close to the base, greatly reducing the inertial load on the platform and lowering the system CoG.
- thanks to the kinematic redundancy of parallel manipulators, a high rigidity and high payload may be obtained with smaller actuators.
- the position errors are averaged instead of added cumulatively, thus parallel manipulators are intrinsically more accurate.

However, these advantages come with the following drawbacks:

- the workspace is usually smaller and can have a complex manifold due to the presence of singularities
- the mechanical design is more complex
- the forward kinematics of the mechanism is usually complex and, depending on the structure, can have multiple solutions

Eventually, exploiting the list of requirements, we selected the design approach examining the features of the two possible designs with respect to our requirements. As shown in Figure 2, the characteristics of the PKM better met our design requirements.

Generally, a PKM is composed by a base connected to a platform through a set of linkages or kinematic chains called “legs”. The position of the actuated joint of each leg is independent from the joints of the other legs, while the position and orientation of the platform is a non-linear function of the position of the leg’s actuated joints. A classical example of PKM is the Steward platform [12]. This complex system has 6-DoF, allowing to independently control the position and the orientation of the platform. For R1 we focused on

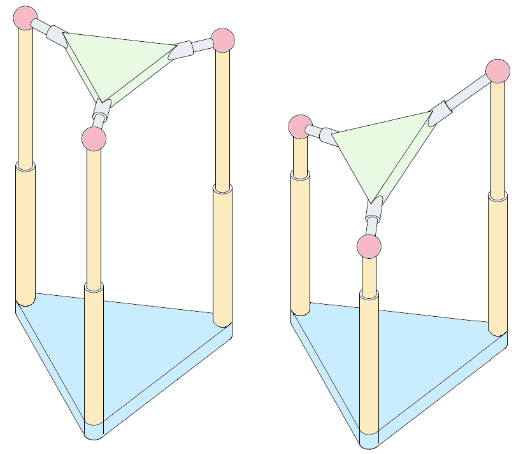

Fig. 3: The conceptual design of the parallel structure in two different configurations. The colors identify the core components of the system: in blue the base, in yellow the linear actuators, in red the passive spherical joints, in gray the passive prismatic joints and in green the platform. When the platform is tilted its center moves also in the horizontal plane.

simpler PKM with only 3-DoF. Among all the designs that can be found in the literature, we tried to identify a solution less affected by the common drawbacks of the PKM. In particular, we sought for a structure with a simple mechanical and kinematic design and a wide workspace with a minimum number of singularities.

The first design that we analyzed is represented by a system with three kinematic chains fixed on the vertexes of an equilateral triangle [13]. The kinematic chains of this PKM are constituted by a passive rotational joint connected to a linear actuator which is connected to the platform through a spherical joint. A similar design, but with a simpler mechanical structure is described in the work [14]. In this case, the legs of the parallel manipulator employ a linear actuator fixed perpendicularly to the base and connected to the platform through a spherical joint followed by a prismatic joint. Our solution is an evolution of the second example. In particular, in our design, the prismatic joint has been modified to reduce the volume occupied by the linear guides[4] and the spherical joints have been reoriented to increase the platform workspace in terms of inclination. These improvements had a great importance for the fulfillment of the requirements 3) and 2) respectively.

The final conceptual design, depicted in Figure 3, is a PKM comprising a base supporting three linear actuators fixed on the vertexes of an equilateral triangle. Each linear actuator is connected to the platform through a passive spherical joint followed by a passive prismatic joint. If

[4]The linear guides in the work [14] are constituted by a slider connected to the spherical joint and a guide connected to the platform. In our design instead, we connected the slider to the platform and the guide to the spherical joint.

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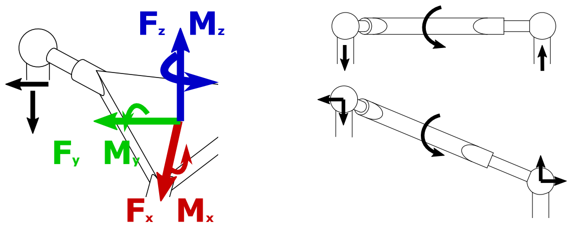

Fig. 4: The left figure: the spherical joints don't produce any reaction moment on the actuator rods. Thanks to this decoupling the only forces acting on the rods are either pure axial loads or radial loads. The right figure: if the platform is horizontal a moment applied to the platform generates pure axial forces on the actuator rods, contrary when the platform is tilted a moment generates also radial forces.

the linear actuators are driven with the same velocity the platform moves vertically maintaining a constant inclination. Conversely, if the linear actuators are controlled with different velocities, the platform can be tilted back/forth or sideways.

C. Loads analysis

To select the actuators and properly design the supporting frame we examined the forces and moments acting on the platform. In particular, the platform is subject to loads due to the mass of the upper-body and loads due to the interaction forces between the robot hands and the environment. The upper-body loads are configuration dependent, and have been estimated through simulations[5]. The interaction loads have been estimated by applying the maximum interaction force on the robot hands[6] for different configurations of the arms. Dynamic loads have been neglected because R1 has not been designed to tackle highly dynamical tasks.

Having estimated the maximum loads acting on the platform it has been possible to solve for the axial and radial forces on the rod of the linear actuators. As depicted in Figure 4, we considered the platform in two different configurations: horizontal (i.e. parallel to the base) and tilted of 30 [deg]. Considering the system horizontal cancels the contribution of roll and pitch moments to the radial forces. Contrary, when the platform is tilted the same moments generate also radial components.

The axial forces have been computed considering the platform horizontal and solving the moment balance equations for the maximum pitch and roll moments and the maximum force F_z. The radial forces have been computed for both the horizontal and tilted configurations. For the tilted configuration we considered the maximum inclination and solved a simple moment balance equation. For the horizontal case we considered the simplified 2D model depicted in Figure 5. In

[5]The mass of each link was estimated based on the list of components belonging to the link itself. The simulation included different scenarios, like for example the robot grasping an object from the floor or an object on an high shelf.

[6]The maximum interaction force has been computed considering the maximum torques of the arm joints.

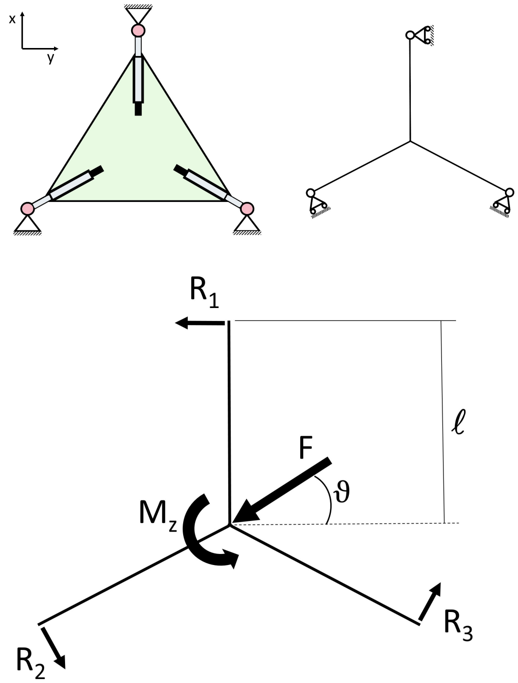

Fig. 5: The top left image represents a 2D model of the platform. The top right image represents the equivalent model, while the bottom image represents its free body diagram.

particular, with reference to Figure 5 (left side), the problem was to compute the x and y components of the reaction force on each actuator rod for a given external horizontal force $\boldsymbol{F} = F_x + F_y$ and a yaw moment $\boldsymbol{M_z}$. Neglecting the friction forces of the prismatic joints linking the spherical joint to the platform, we can infer the model of Figure 5 (right side) together with its free body diagram (bottom). Being the system statically determinate and completely constrained, we can solve for the radial forces considering the following system of equilibrium equations:

$$\xrightarrow{+} \sum\nolimits_y : -F cos(\vartheta) - R_1 + \frac{1}{2}R_2 + \frac{1}{2}R_3 = 0 \quad (1)$$

$$\uparrow + \sum\nolimits_x : -F sin(\vartheta) - \frac{\sqrt{3}}{2}R_2 + \frac{\sqrt{3}}{2}R_3 = 0 \quad (2)$$

$$\circlearrowleft + \sum\nolimits_M : M_z - F cos(\vartheta) l + \frac{3}{2} l \left(\frac{1}{2}R_2 + \frac{1}{2}R_3\right) = 0 \quad (3)$$

D. Mechanical design

The work flow followed during the development of the torso joint, and R1 in general, involved a close collaboration between the style team and mechanical team. Thanks to this collaboration it has been possible to quickly explore different layouts.

During the design of the frame we had to take into account that the linear actuator rods can not bear radial forces. To solve this issue we designed custom linear guides to support and guide the linear actuator's rods. The design has been carried out considering the radial forces computed in the previous section. The torso frame has been designed

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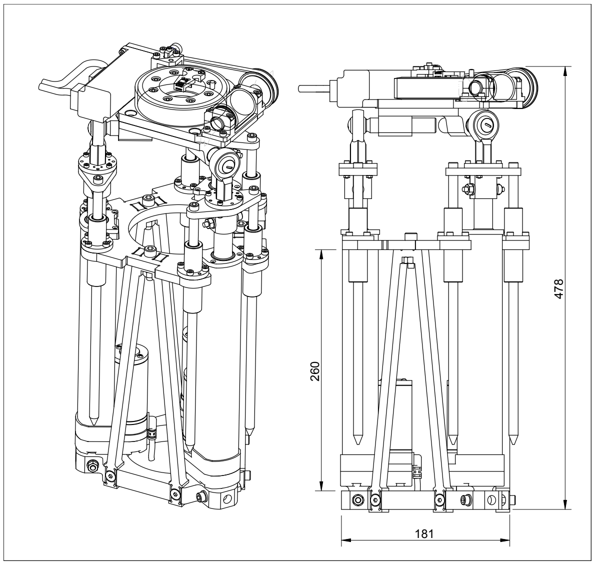

Fig. 6: The final layout of the torso joint. The figure shows the main dimensions of the system.

to be easily assembled and be cost effective. The selected design is based on a truss structure comprising three triangles connecting the base to the top plate. All the main components of the frame, the base, the trusses and the top plate have been designed to be easily manufactured with a water-jet (or laser) cutting machine. The structural stiffness is ensured thanks to the adoption of recessed joints to join the components together. The linear actuators have been selected as affordable Commercial Off-The-Shelf (COTS) systems, while ball bearings have been replaced with plastic bushings.

The fourth DoF, i.e. the yaw joint, has been designed using a worm-gear transmission actuated through a belt by a brush-less motor.

The final layout of the system is depicted in Figure 6.

III. Evaluation

The evaluation of the proposed solution has been accomplished by assessing the fulfillment of the design requirements and by testing a first prototype of the torso joint.

A. Prototype description

A first prototype of the torso joint was built to test and validate our design. We selected linear actuators manufactured by MOTECK to construct the prototype. The actuators comprise a DC motor that drives an ACME[7] lead screw connected to a rod, and can provide a peak force of 400 [N]. The supporting guides have been constructed using aluminum anodized bars sliding inside plastic bushings inserted in custom aluminum components fixed to the frame. All the custom components of the guides have been machined in aluminum, while the custom frame components have been cut from an aluminum sheet using a water-jet cutting machine[8]. The spherical joint and the prismatic joint are produced by IGUS. The spherical joint is entirely made of plastic, while the prismatic joint is constructed using an anodized aluminum bar sliding inside of a plastic bushing. The screw that is used to lock the shaft of the prismatic joint to the sphere of the spherical joint is a custom component that has been specifically designed to prevent any possible interference between the screw head and the sphere housing. In particular, the head is machined to be spherical with a radius equal to the radius of the joint sphere (see Figure 1). The yaw joint comprises a 100 [W] electric motor by MECAPION, and a worm gear reduction stage by IGUS with plastic gear.

The motors are controlled using the electronic boards developed for the iCub project [15]. The primary board is an embedded microcontroller-based device that controls 2 external motor-driver cards. In particular one motor-driver card powers two linear actuators of the parallel structure, while the second one powers the third linear actuator and the brush-less motor of the yaw joint. The position of the linear actuator's rod is measured, after an initial calibration, exploiting two hall sensors integrated in the linear actuators, while the angular position of the yaw joint is measured using a custom absolute encoder.

B. Design evaluation

The design evaluation has been carried out to determine how the system performed with respect to the design requirements. We exploited our 3D modeling software to analyze the mass properties and platform RoM. The cost estimation instead, has been assembled considering commercial components, custom components, assembling and wiring. For commercial components (i.e. motors, speed reducers, bushings and electronic boards) we created a cost database detailing how component prices varied with the quantity. For custom components we quoted each part considering material, recurring and non-recurring costs. Wiring and assembling have been estimated based on our experience with the iCub robot. The quotations have been estimated considering the most competitive labor costs.

The results of the design evaluation are the following:

- The final cost of the whole structure has been estimated for the target production of 2000 R1. Table I summarizes the quantities for each component together with the final cost of the system.
- The workspace of the parallel structure is represented in Figure 7. The pictures detail the range of motion of the system with respect to its degrees of freedom.
- The novel arrangement of the prismatic joint connected to the platform greatly reduced the volume occupied by the system. As a consequence the entire system is completely enclosed inside of the surfaces given by the style team.
- The weight and the center of mass of the system have been analyzed using our CAD software. As shown in

[7]The ACME thread form has a 29° thread angle with a thread height half of the pitch; the apex and valley are flat.

[8]Some of these components have also been reworked to add threaded holes.

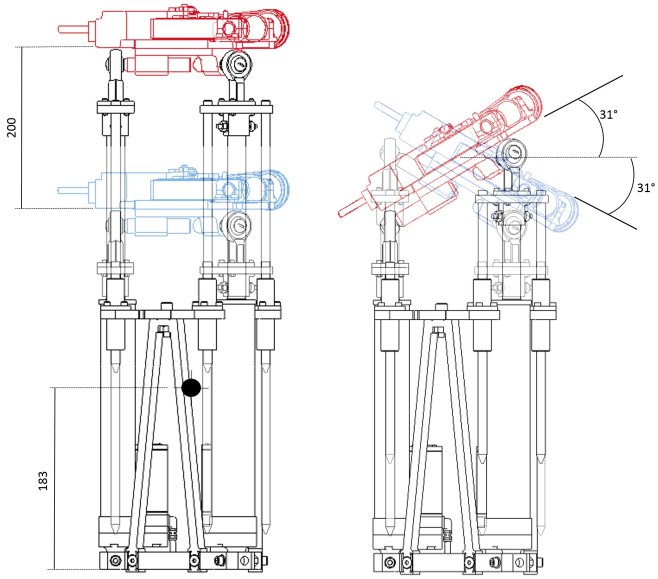

Fig. 7: On the left the heave workspace is depicted by superimposing the fully extended (red) configuration over the fully retracted (blue) configuration. Furthermore the position of the CoM computed for the fully retracted configuration is shown by the black point. On the right the roll (or equivalently, the pitch) workspace is depicted by superimposing the maximum positive and negative platform inclination.

Item	
Category	Price [€]
Commercials	455
Assembling	50
Wiring	50
Custom components	880
TOTAL	1435

TABLE I: The table lists the components and manufacturing costs for one torso joint with 4 DoF when mass produced.

figure 7 the center of mass is contained in the lower half of the system assembly, and the total weight is about 8.5 [kg].

- Thanks to the adoption of a parallel structure all the actuators are fixed to the base, relieving the platform from any inertial load.

C. Prototype experimental testing

The purpose of the experimental tests conducted on the prototype was to asses the mechanical performances of the system, and not to validate the controller itself. For this reason we develop a simple controller based on the inverse geometrical model of the parallel mechanism. In particular, with respect to Figure 8 and following a similar approach to the one proposed in [5], we defined:

- $\boldsymbol{X}$ as the set of generalized coordinates describing the position of the platform. We considered the platform center $\boldsymbol{C}$ and three angles to represent its orientation;
- $\boldsymbol{A}$ and $\boldsymbol{B}$ as the end of the legs connected respectively to the base and to the platform;

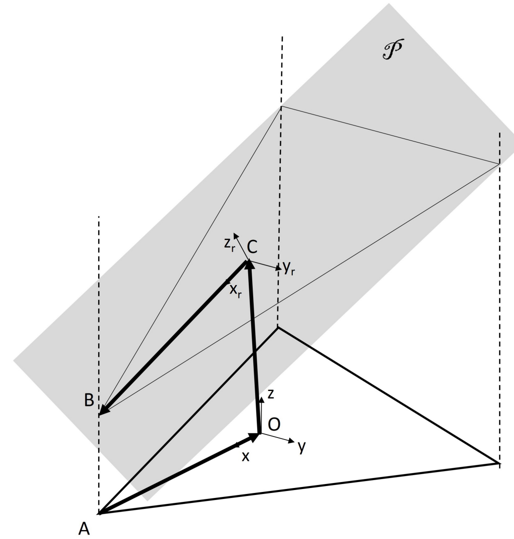

Fig. 8: The model of the parallel kinematic structure.

- $\boldsymbol{O}$ as the origin of the base reference frame.

The problem to be solved was to determine the vector $\boldsymbol{AB}$[9] for each leg:

$$\boldsymbol{AB} = \boldsymbol{AO} + \boldsymbol{OC} + \boldsymbol{CB} \tag{4}$$

The vector $\boldsymbol{CB}$ is known in platform frame, but can be expressed in base reference frame by exploiting the rotation matrix $boldsymbolR$ calculated from the orientation parameters.

Eventually, in our system the stroke of the linear actuator can be computed by subtracting the height of the platform in its lower position (see Figure 6) from the length of the vector $\boldsymbol{AB}$.

We focused the evaluation on accuracy and repeatability of the parallel structure. The experimental tests have been performed as follows. A set of platform poses has been obtained sampling a desired platform trajectory expressed in Cartesian space. For each pose the equivalent linear actuator strokes have been computed exploiting the mapping described by the inverse geometric model. Eventually the joint space trajectories have been used to drive the linear actuators thanks to a simple PID control loop.

We generated a chest trajectory involving both the extension and the tilting of the torso platform. Subsequently we repeated the same motion for 15 cycles. To measure the position and the orientation of the chest in Cartesian space we used a motion capture system by VICON. As depicted in Figure 9 4 markers have been fixed to the robot chest, while other 6 markers have been fixed to the base of the robot. We exploited the 6 base markers to retrieve the position and orientation of the robot root frame. Figure 10 represents the average velocity of the chest during

[9] Observe that it is also possible to derive the equation of the plane P passing through the platform. Subsequently since the linear actuators are fixed perpendicularly to the base, it is possible to derive the point $\boldsymbol{B}$ by intersecting the plane P with the normal to the base passing trough the vertex of the base triangle.

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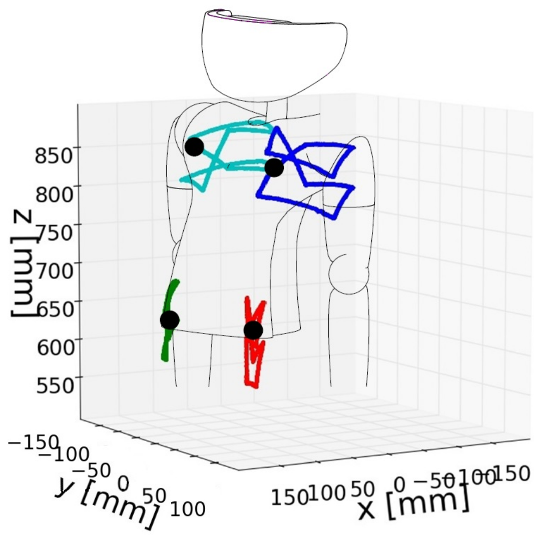

Fig. 9: The four markers have been fixed at two different heights on the chest of R1. For each marker is also plotted the trajectory measured by the motion capture system.

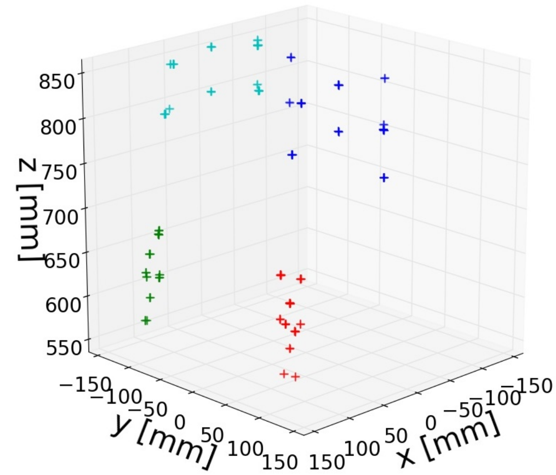

Fig. 11: The points are obtained by overlapping the measured position of the markers over the 15 cycles for 10 different chest poses. In Figure 12 is depicted a magnification of the red marker.

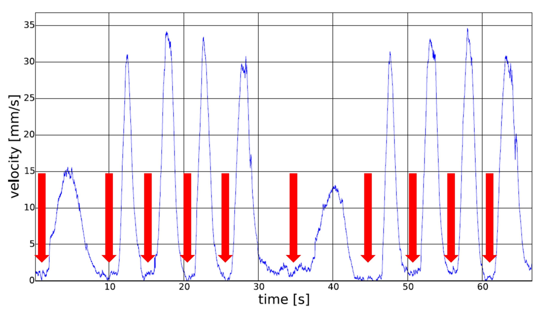

Fig. 10: The average velocity of the chest during one cycle. The peak chest velocity is 35 [mm/s]. During each cycle the platform has been stopped for a few seconds in 10 different poses (red arrows). For each pose we evaluated the repeatability (Figure 11) and accuracy (Figure 13).

one complete trajectory cycle. As depicted in Figure 11, we evaluated the repeatability by comparing the measured position of the chest markers for 10 different poses in each cycle. The accuracy, shown in Figure 13, has been evaluated by comparing the measured position of the markers with the desired position.

The yaw joint has been tested independently by implementing a simple PID loop controlling its angular position.

IV. Conclusions and Future Work

In this work we presented the design of a novel torso joint for our humanoid robot R1. The torso has been designed successfully accomplishing a list of requirements that we created during the conceptual design of R1. The system is based on a parallel kinematic structure with 3 DoF that has been optimized to meet our design requirements. Eventually, a fully working prototype of the torso has been built and tested. In particular, we evaluated the accuracy and repeatability of the parallel kinematic structure. The evaluation has been performed on four checkpoints fixed to the robot chest. No hand position evaluation has been performed because the chest and arm frames have been constructed mainly using plastic, and the arm deflection would have further worsen the result of the tests. One possible solution to cope with the accuracy error of the hand could be visual servoing.

A. Lesson learned

The development of the R1 torso has been a challenging opportunity to learn and improve our skill in humanoid robot design. In particular the most important lessons that we learned are the following:

- the strict cost constraints forced us to follow different design approaches. The parallel design allowed to use affordable actuators, reduce size and weight. The plastic bushings and the plastic spherical joint adequately replaced the metal counterpart, while water-jet cut components replaced expensive CNC machined parts;
- R1 is our first humanoid robot with a parallel kinematic structure. We learned that PKM can be used effectively to design core components, like for example the torso.
- for this project the style of the robot and its underlying mechanical structure were developed jointly; this development process further complicates the design process of the robot but is crucial for obtaining an overall aesthetically pleasing result.

B. Future work

The first prototype of R1 has been built and is currently under testing. Future work will mainly focus in analyzing the forward and inverse kinematics of the parallel structure, improving the mechanical design to further reduce the cost and increasing the accuracy of the system.

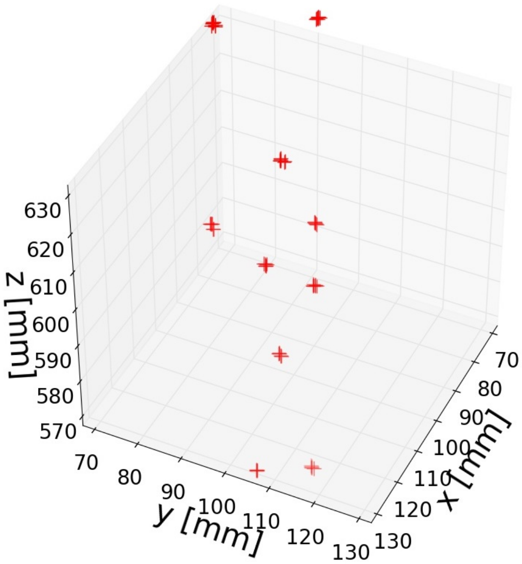

Fig. 12: The points represent the overlapping measurement for one chest marker. The repeatability for this marker is within 2.5 [mm].

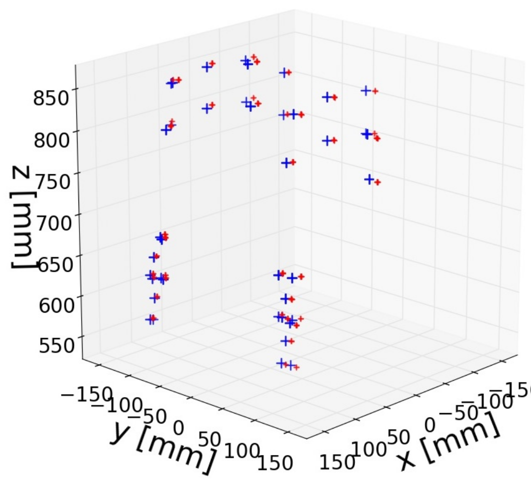

Fig. 13: The red points represent the measured position of the marker. The blue points represent the desired position. The average accuracy is within 11 [mm].

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