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End-Effectors Changer Design for Humanoids

Julien Roux*, Jean-Baptiste Izard, Arnaud Tanguy, Hiroshi Kaminaga, Fumio Kanehiro
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Abstract—Almost all (not to say all) existing humanoids have not been designed with the ability to change their end-effectors (head, feet and hands) on-the-fly. Inspired by the tool-changing mechanisms in robotics automation and manufacturing, we propose an end-effectors changer mechanism suitable for humanoids. This letter explains why enabling humanoids with such a technology is important and why existing tool-changer mechanisms are not adapted. The proposed changer mechanism is not actuated. Yet, it does not require human intervention to assist the change of end-effectors. We assess our mechanism through a comparative study with existing tool-changers and demonstrations with the HRP-4 humanoid. We claim that our idea could be a new turn in the design of future humanoids and open perspective to modular sizing of robots. The proposed mechanism can possibly apply to animaloids to some extent.

Index Terms—Humanoids, animaloids, automation, end-effector changers, mechanical design.

I. INTRODUCTION

AIMING at paving the way to humanoids in manufacturing, see e.g., [1]–[3], we achieved *in-situ* complex demonstrators with terrain real-use cases. Tasks associated with these use-cases were categorized as non-added value for the human workers. A large number of these tasks are achieved with tools and the few achieved with bare hands did not require high dexterity. Designing humanoid robot’s grippers with the dexterity and the degree-of-freedom of that of a human hand is a very challenging problem, especially if one considers the weight and size as design constraints, e.g. [4]. Therefore, it is questionable whether designing sophisticated hands is the only-way-to-go solution in an industrial context.

Since the past two years, there has been a booming of new humanoid platforms. Encouraged by the amazing achievements of Boston Dynamics’s Atlas humanoids and the reliability of Honda’s ASIMO, new humanoid robots have been disclosed by large companies like for example Tesla and Kawasaki Heavy Industries. Others have emerged from dedicated medium size new companies. For example, Agility Robotics is deploying humanoids for logistics applications. We are also paired with Kawasaki Robotics to design and deploy manufacturing and social humanoid robots. In this letter, we discuss one part of the design consisting in solving

a shortcoming observed in previously mentioned applications: the need for different grippers, feet, head and even sometimes limb’s length for the same application domains. Almost all existing humanoid robots come with unchangeable mechanisms to attach the gripper and feet and head, often designed once for all. It is well known that bipedal mobility poses high constraints on the end-effectors in terms of weight, payload and connectivity that makes it difficult to design sophisticated systems that do it all. Even if general purpose humanoid robots (GPR) is an interesting perspective in terms of both technological and fundamental aspects, we could also think on humanoids that can change autonomously and quickly appropriate end-effectors such as entire grippers, feet, heads... or other tools to match specific task as we human do with different tools that are all extensions of our own ‘end-effectors’ (e.g., drill, dedicated shoes, night-vision, etc.).

In the robotic industry and manufacturing, this idea is not new. Tool-changers have been used in robotics since long, see Sec II. Tool-changers are a very practical technology to increase manufacturing efficiency and performances. Many tool-changers for industrial robotic arms or cobotics are available, but they are not suitable for humanoid or animaloid usage because of the many reasons explained in Sec II.

In this letter, we propose the design of a new tool-changer mechanism suitable for humanoids. Yet, we rather named it *end-effector changer* because it does not content in changing tools and grippers, but extends to feet and head. The new design, thoroughly documented in Sec. III, accounts for all the shortcomings enumerated in Sec. II, e.g., light-weight, no-actuator embedded, large precision tolerance in mounting and dismounting, no need for human operator assistance, etc.

Our end-effector changer is demonstrated using HRP-4. Several engineering efforts were dedicated to make the necessary changes in mechatronics, low-level software, high-level software... such as swift updating the URDF model and the task-space controller (Sec. IV). Resulting knowledge is gathered and shared in Sec. V, with perspective on potential improvement and future work in Sec. VI.

II. BACKGROUND

A. Tool-changing technology

Since the mid-1980s, tool-changer mechanisms (TC) are used in automation industries to increase the efficiency and versatility of CNC machining [5]–[7]. Likewise, automation robots’ capabilities and versatility are enhanced thanks to the development and commercialization¹² of new TC.

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¹<http://triplea-robotics.com/tool-changer/>

²<https://smartshift-robotics.com/tool-changer/>

For instance, in [8], the polishing bits on a robotic arm are changed using TC to improve the productivity of a die polishing station. In [9], a small electrically actuated TC enabling autonomous tool change and electric pass-through is devised and tested. It comes with internal actuation and sensing for its operation but has a complex design. In opposition, [10] introduces a simple passive design for robotic arms with no actuators. The system relies on springs and a clever locking mechanism that triggers when inserting the tool back in the tool station but lacks electric pass-through; also focusing on increasing its tolerance to positioning error for tool change. Similarly, in [11], the authors designed and integrated a resilient TC for a robotic arm mounted on a mobile platform that inspects corrosive and radioactive tunnels. It is robust and cheap as it has to be often discarded due to contamination but lacks electric connections. [12] presented a highly customizable modular end-effector system with pneumatic, data, and electric connections. This TC uses a solenoid as part of its locking mechanism. Besides, its size may reduce the payload as it will increase wrist torques. In [13], an automatic TC for robotic arms is designed and analyzed. It is 3D printed and has no electrical connections. It is specifically designed for UR-10 robots. In [14], TC were used for micromanipulation robotics at a scale between 1 and 100 μm .

TC is also found in docking for modular robotics [15]. Self-reconfigurable modular robots use simple modular robots (usually with only 1 or 2 dof) that dock together to generate more complex behaviors and reconfigure their structure to adapt to different situations. In [16], the authors reviewed existing docking mechanisms and methods. Due to the simple structure of each robot module, most docking systems rely on an inner actuation (motors for mechanical coupling, electromagnets for magnetic coupling...) to lock and unlock. Similarly to TC, coupling tolerances are of major importance.

When considering TC for humanoid robots, technical problems presented in [1], e.g., weight limits, actuator limits, on-the-fly model updates for the controller... are to be accounted for. In this letter, we design and integrate end-effector changers for humanoid robots. We assume the end-effectors are stored at a tool station. It is rather an industrial fact that can be relaxed.

In this case, SLAM [1], [3] is a typical solution to locate the tool station and plan motion toward it. When changing its end-effectors, a humanoid operates under balance constraints that are extensively studied, e.g., [17]. Then, as the end effector approaches the tool station (down to 1 cm) visual servoing can be used. In [18], visual servoing is used for tool changing and is shown to be faster than having an operator teach the robot how to change the tool. Finally, contact initiation, contact detection, and contact force control during engagement and disengagement motions must be monitored [19], [20]. All these modules are integrated in Sec. IV.

Furthermore, the design of a humanoid end-effector changer shall account for the limitations of existing TC technologies.

B. A comparative study with two different tool-changers

This section discusses our tests and initial efforts to integrate end-effector changers on our humanoid by implementing two commercially existing solutions .

There are many tool-changers designed such that the tool is mounted and dismounted by an operator. We refer to them as *manual tool-changers*. The Shunk manual tool-changer³ has a two-step release: first a button is pulled, then an arc-like handle is rotated for more than 90 deg. Not only is it not suitable for humanoids because of its weight, but it also cannot be adapted to automate its opening/release by the humanoid itself. For the OnRobot⁴ and Kosmek⁵, the mechanism is triggered by pressing a button to insert/release the tool. Meanwhile, the tool must be held properly to not fall. We tested the OnRobot TC with our humanoid (Kawada Robotics HRP-4). The integration was straightforward (providing few adjustments on the robot), as only some simple interfaces had to be designed. Furthermore, they provide a lot of convenience by allowing the robot to be used in many different settings. However, operating it requires the dexterity of the operator hand, it can also not be operated by the humanoid itself. Moreover, the humanoid might have end-effectors embedded with tools/grippers that cannot operate the release and mounting of the manual tool-changer mechanism as would a human operator do. For example, it cannot press the release system while holding the tool to remove it (an operator would need both bare hands to insert/release a tool).

Kosmek also provides a TC that relies on the tool station to lock/unlock itself⁶. Similar to the design presented in [10], the TC is locked/unlocked as the tool is removed from/stored in its station using contacts with the station to actuate the TC. This method uses the force generated by the robot actuators to lock/unlock the TC. However, the force needed by the TC to be locked/unlocked can be greater (up to 75 N) than what the robot can provide in the locking/unlocking configuration. To compensate for this issue, we used a TC from the same brand with a similar locking mechanism that uses an electric actuator to lock/unlock itself. Then, vision is not precise enough to position the end-effector for the TC to lock itself (required precision is 1 mm, see Table I). In order to successfully engage the TC, we relied on force sensing and implemented peg-in-hole strategies [19], [20]. We performed both humanoid gripper and foot changes with this TC. However, the added weight and actuators is clearly not negligible and the integration of the TC electronics was extremely difficult to handle. Moreover, it showed many problems when trying to lock, as perfect alignment was difficult, especially for the feet. Also, as its rating is not high enough to bear the full weight of the robot, trying to walk using this TC would certainly damage it.

To sum-up this section, relevant data about reviewed tool-changers is provided in Table I. Humanoid robots weighs above 50 kg; existing tool-changers are not designed for such a payload when used at the feet of the humanoid.

C. Limitations and design constraints

The trials we conducted with the two most most suitable TC, highlighted a set of constraints for tool-changers when

³https://schunk.com/us/en/automation-technology/change-systems/shs/c/PGR_3365

⁴<https://onrobot.com/en/products/quick-changer>

⁵https://www.kosmek.co.jp/php_file/eng_product_page.php?no=310_01_01

⁶https://www.kosmek.co.jp/php_file/eng_product_page.php?no=359_01_01

TABLE I: Existing TC data (extracted from data-sheets). Weights account for both robot and tool side. Required locking precision is the allowed positioning error when locking the TC.

model	weight / payload	required precision	disadvantages	pneumatic / electric connexions
Schunk manual (SHS 050)	350 g / 11 kg	1 mm	hard to handle	4 / no
OnRobot Quick Changer	200 g / 20 kg	-	engagement trajectory	no / yes
Kosmek manual (SXR)	≈ 230 g / 10 kg	-	pressing force to unlock	no / no
Kosmek mechanical (SMR)	≈ 650 g / 12 kg	±1.0 mm 1.2 deg	important contact forces to operate	up to 4 / optionnal
Kosmek electrical	≈ 400 g / 3 kg	±1.0 mm 1.2 deg	electronic integration	up to 4 / optionnal
Proposed hand EEC	≈ 130 g Sec.III-B	±5.0 mm > 5 deg	prototype	0 / yes
Proposed foot EEC	≈ 120 g Sec.III-B	±5.0 mm > 5 deg	prototype	0 / yes

applied to humanoids with the aim of changing end-effectors other than tool or grippers (that is, also feet and head).

◦ To not increase the overall humanoid’s weight, the TC must be lightweight and as flat as possible to not lengthen the limbs. Consequently, the robot should operate the TC without an extra actuator. Indeed, adding an actuator to the changer mechanism would substantially increase its weight and require the integration of extra electronics not only inside the TC, but also at the level of the robot motor drivers and command.

◦ Since a humanoid has multiple limbs, a different end-effector can be used to operate the TC of another one. Therefore, the design shall account for the operating limb to have a variety of possible end-effectors. As a consequence, such a design should also be easily human-operated.

◦ In our preliminary tests we were able to reach a whole-body (floating-base) positioning of ± 5 mm and ± 5 deg of precision with a low-precision humanoid. Hence, the design shall allow for such positioning errors when initiating the engagement of the TC.

◦ The TC should be able to withstand the forces and torques of the normal operation of the robot. For this, a single design must account for three different use-cases of the TC:

- hands* relatively low-payload end-effectors that often accommodate many possible grippers and/or tools;
- feet* high-payload end-effectors that support the weight of the robot and its dynamics during walking;
- head* much lower payload end-effectors equipped with sensors that send a lot of data, such as cameras. They would certainly have normative cabling different from those of the feet and hands.

Given these constraints and requirements, the data from Table I, and the preliminary trial results with two representative existing TC, we devised a new end-effector changer.

III. DESIGN OF THE END-EFFECTOR CHANGER

We describe the design and the usage of a new end-effector changer (EEC). The design strain-stress is initially evaluated by means of finite element analysis (FEA).

A. Mechanism and operation phases

The EEC is made of 3 assemblies (Fig 1): (i) the tool side (Fig. 1c) with the pin/shaft coming out of it, attached to each end-effector/tool; (ii) the robot side (Fig. 1b) mounted on the robot instead of the regular end-effector; and (iii) the locking bell (Fig. 1a) rotating around the robot side to lock and unlock the EEC when the tool and robot sides are engaged.

The engagement of the EEC is as follows: first, the spherical tip of the pin on the tool side makes contact with the funnel on the robot side. Then, the tip slides along the surface of the funnel until the center is reached (Fig. 2a), locking the relative translations of the two sides along the plane normal to the z -axis. As the pin is pushed inside a plain bearing both the z -axis of the tool and robot sides become collinear, letting only rotation and translation around the common z -axis possible. The pin is inserted until surfaces A and B are in contact. Next, both sides rotate relatively to each other until tab C enters slot D. This ensures the correct orientation for the final translation along the z -axis without damaging the electrical connectors. At this point, surfaces E and F are in contact (Fig 2b). A rotation until contact between surfaces G and H will end the engagement of the two sides by preventing the tool side from moving back along the z -axis (contact between surfaces I and J) (Fig. 2c). The locking of the mechanism is done by rotating the bell around the robot side which pushes the teeth of the robot sides in the feet of the tool side (Fig. 2d). This locks the mechanisms by preventing the final rotation along the z -axis.

Note that the bell bears no load as all efforts are transmitted through the tool and robot sides. Our design comes in 3 variations: (i) a standard version for lower load limbs as the hands of a humanoid robot, (ii) a bigger version to bear greater loads as the ankles of a humanoid robot, and, (iii) a final one allowing the passing through of USB type-C cables which allows for more information passing through like a camera output with limited loads (Fig 7). All these versions use similar engagement motions and locking mechanisms. They differ mostly in terms of sizes (e.g., the bigger version is wider to support higher torques) and part arrangement. For both standard and high payload versions, the electrical connection supports up to 24 wire connections and is designed to provide EtherCAT-like connection capabilities. The connections are routed through each side of the EEC using flexible PCBs. When the EEC is locked, spring-loaded pins link both sides electronically.

B. Stress evaluation

To evaluate the design of the EEC, we first realize a Finite Element Analysis. We studied the following cases for both the hand and foot EEC (we do not expect the head to have a high payload and substantial external forces applied to it):

- Traction/Pulling along the z -axis is transmitted through the contact between surfaces I and J;
- Compression/Pushing along the z -axis is spread across the three E and F surface contacts Fig.3a;

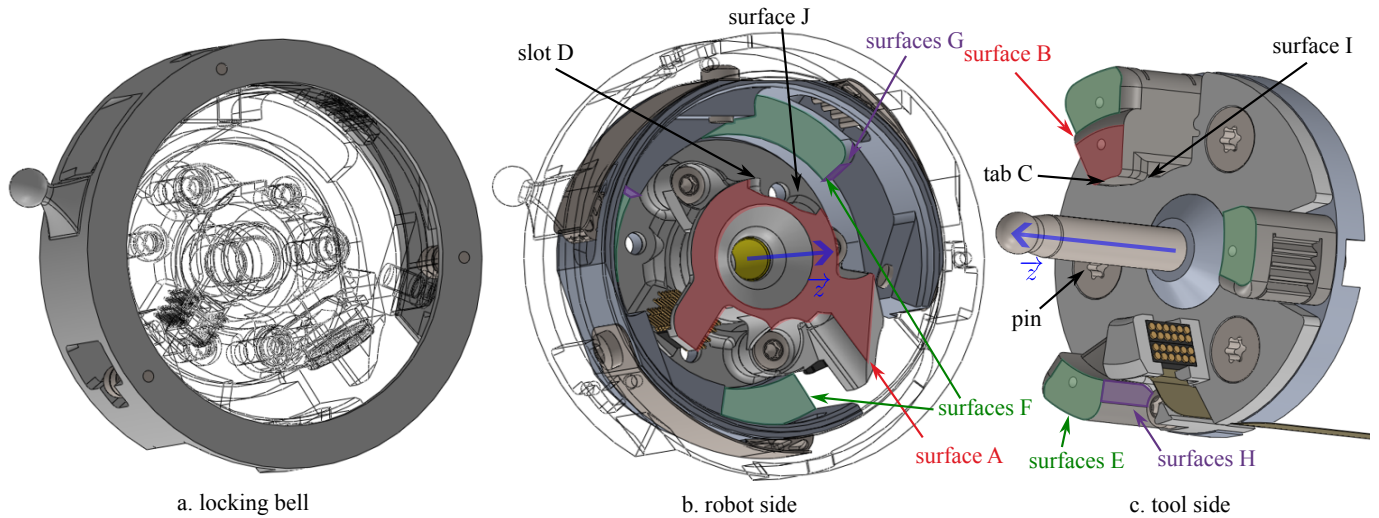


Fig. 1: Subassemblies of the proposed design. On the bell, the small sphere is used to lock/unlock the EEC. The surfaces are color-coded: surfaces of the same color on both the robot and end-effector/tool sides will match once the ECC is locked. Surfaces E, F, G, and H are each a set of 3 similar surfaces spread around the ECC.

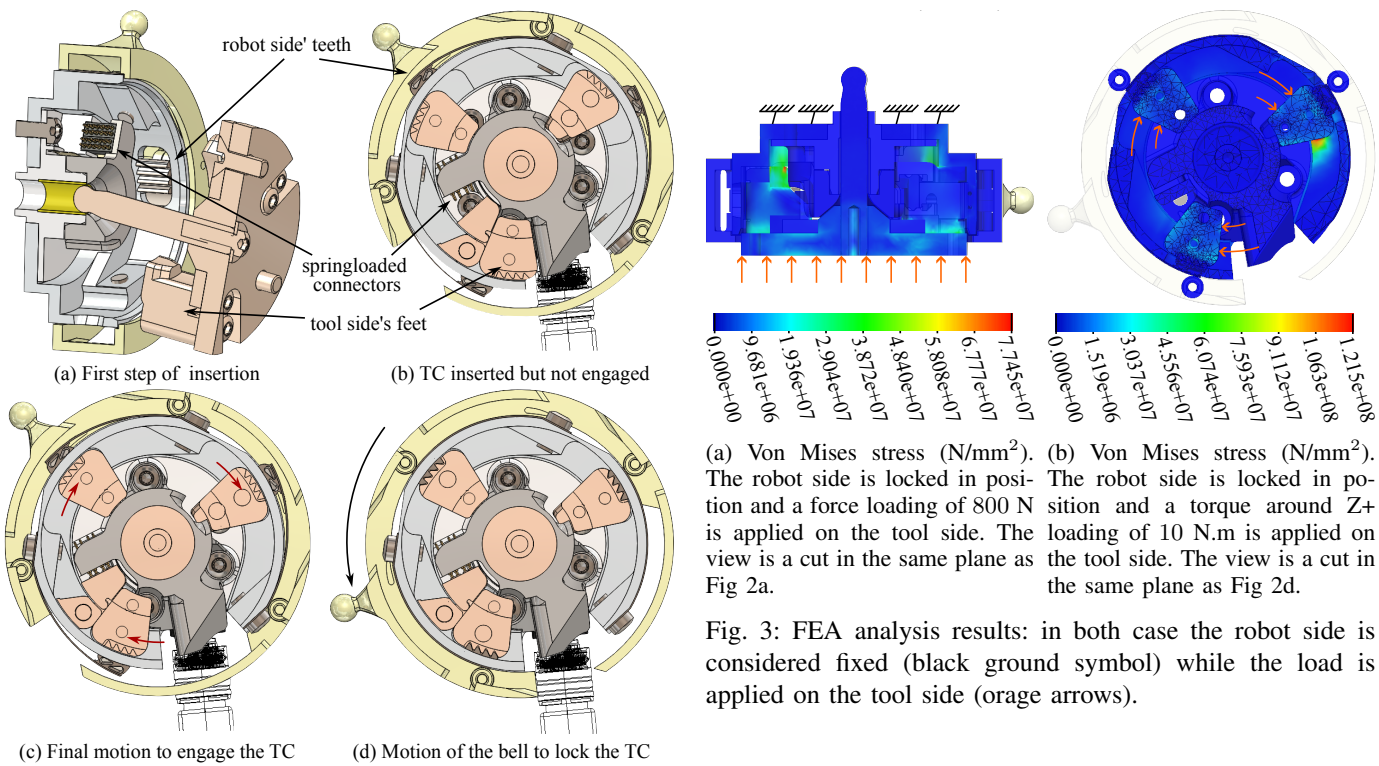


Fig. 2: Different steps of EEC engagement. Sub-figure 2a is a slice in a plane containing the z -axis. Sub-figures 2b, 2c, and 2d are slices normal to the z -axis at the bottom of the pin looking from the end-effector/tool side toward the robot (effector) side. In each sub-figure the parts of the EEC are color-coded in the same way.

- Torque along the z -axis is transmitted, depending on the direction, by the teeth in the feet (Z-) or the contact between surfaces H and G (Z+) Fig 3b;

Fig. 3: FEA analysis results: in both case the robot side is considered fixed (black ground symbol) while the load is applied on the tool side (orange arrows).

- Forces and torques in the plane normal to the z -axis are transmitted through the pin.

Table II gives results for the hands and head EEC and Table III. The max load is the load for which at least one part reaches a Von Mises stress equal to its yield strength. The target load is the value set as a target for our design (twice the limits of the force sensor in that loading case).

Material-wise, two cases are considered: (i) 3D printed polyamide (SLS) (yield strength 48 MPa) for fast and cheaper prototypes, and (ii) Aluminum (yield strength 275 MPa) for more robust parts. In both cases, the pin and feet are made of

TABLE II: Result from FEA on hand/head EEC.

Load case	Target load	Material	Max load
Traction Z	1160 N	Polyamide	80 N
		Aluminium	550 N
Compression Z	1160 N	Polyamide	650 N
		Aluminium	> 1160 N
Torsion Z+	20 N.m	Polyamide	11.2 N.m
		Aluminium	> 20 N.m
Torsion Z-	20 N.m	Polyamide	≈ 2 N.m
		Aluminium	> 20 N.m

TABLE III: Result from FEA for foot EEC.

Load case	Target load	Material	Max load
Traction Z	800 N	Polyamide	100 N
		Aluminum	100 N
Compression Z	800 N	Polyamide	> 800 N
		Aluminum	> 800 N
Torsion Z+	24 N.m	Polyamide	10 N.m
		Aluminum	> 24 N.m
Torsion Z-	24 N.m	Polyamide	5 N.m
		Aluminum	> 24 N.m

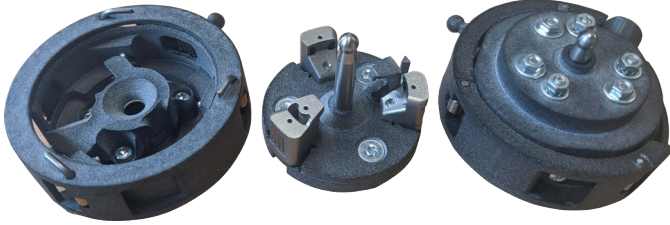


Fig. 4: Prototype of the end-effector changer. From left to right: robot side, end-effector/tool side, mounted and locked tool-changer (both robot and tool side).

steel (yield strength 300 MPa). From FEA, the prototype EEC made with polyamide cannot reach the target loads (this is confirmed by early trials). In the pulling/traction on the z -axis case, the effort is transmitted through only one “foot” (there is only one set of contact for surfaces I and J) which results in a low maximal load in that loading case. Using stronger materials such as aluminum improves the results. Yet, the traction/pulling case seldom happens and the simulated limits are still above the usual load on our humanoids. Thus, prototypes of this design were manufactured and tested to evaluate its performance relative to the other design constraints.

IV. EVALUATION ON A HUMANOID HRP-4

Our proposed EEC is integrated into our HRP-4 humanoid. In this section, we discuss how we implemented the use of an end-effector changer. A video of the resulting demonstrations is a multimedia part of the paper.

A. Mechatronics integration and mounting

As shown in Fig. 4, prototypes of our end-effector changer design are made using 3D printing. Most parts are made of 3D printed polyamide (SLS) (dark gray). The feet on the tool side are printed in steel (shiny gray). The pin has been machined as its shape is not complex.

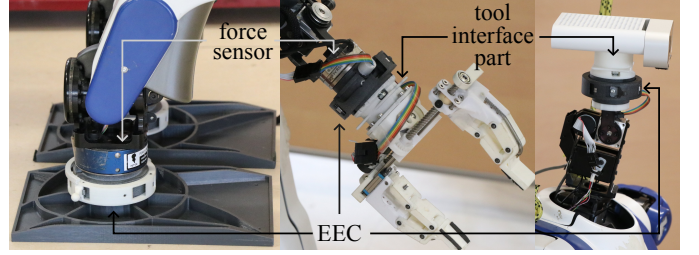


Fig. 5: Prototype EEC mounted on humanoid HRP-4 (from left to right: feet, hand, head).

Hardware integration: Figure 5 illustrates how the EEC is mounted on the robot. The robot side of the EEC is where the end-effector was previously attached. Our EEC uses similar TC mounting standards. On the end-effector/tool side, an interface part is added as no standard interface exists for the moment. This part also provides a simple way to store a given end-effector once detached from the robot. Details are given about this part and the design of the tool stations in Secs. IV-B, IV-C and IV-D.

The electrical and data connection are soldered to both sides of the changer mechanism. In our case, the used gripper has one actuator which uses 6 cables connections (2 for power supply and 4 for the encoder data). The design can offer up to 24 wires using an internal flexible PCB.

Behavior integration: When the robot needs to change an end-effector/tool, it has to reach the tool station (or any other location) where tools and end-effectors are stored. As mentioned in Sec. II, this can be done using SLAM, e.g. [1], [3]. Once the robot stands close to the tool station, the desired end-effector/tool can be located using vision or any other sensor. The changing of the end-effector/tool happens in two phases. First, the current tool is unlocked, stored in the tool station, and disengaged. Then, a new tool is attached, released from the tool station, and locked. With visual servoing, the end-effector can be precisely positioned close to the station before starting the physical interaction that relies on force feedback from the humanoid embedded force sensor and the known geometries of the end-effector/tool and station.

The tool change sequence is integrated into our task-space control framework⁷ presented in [1]. Vision-based positioning tasks move the changer mechanism within the tolerance distance of the tool station. Admittance tasks regulate the contact forces. Finally, a balance task guarantees that the robot keeps its balance while the robot changes end-effectors/tools. When vision is not possible (e.g., the feet can’t be seen), kinematics and force sensing are used to make contact with the environment and estimate the precise location of the tool station, see Sec. IV-C. In this case, the geometry of the tool and tool station are accounted for to generate the desired behavior.

The distinction between arms and legs comes from our available platform. Indeed, the camera is on the head of the robot, and the feet cannot appear within its field-of-view (FoV). Sec IV-D details head change.

⁷https://jrl-umi3218.github.io/mc_rtc/index.html

A different conception of the humanoid can account for the possibility of embedding a changer mechanism to facilitate the integration of our proposed technology.

B. Arms' end-effectors changing

Arms' end-effectors changing is made using vision for the final approach and admittance control when there is contact. At the level of the arm terminal point, two end-effectors are exchanged on the fly:

- a simple un-actuated end-effector providing flat contact that the robot can use in multi-contact locomanipulation (Sec. IV-C);
- an actuated gripper with a complex shape used in [1].

First, the kinematic and dynamic models of the robot have to be updated online in the control framework. Contact surfaces that the robot can use to interact with its environment and collision shapes must also be updated. Then, the lower-level controls and firmware have to power on (resp. off) the added (resp. removed) joint. In our robotic firmware it is possible to turn off each motor independently as they are each directly connected to the main control board (this may be harder to implement in platforms that use protocols such as EtherCAT). All these technicalities are implemented and enabled through robust coding. Updates happen when the EEC is engaged and unlocked while the end-effector is in the docking (i.e., storage) station. These parameters differ when engaging/disengaging the EEC and when storing/releasing the end-effector.

Due to the kinematics and active self-collisions of the robot, there is a singular phase where it is impossible to lock the EEC while the end-effector is stored in a station. Therefore, the EEC design makes it possible to remove the end-effector from the docking station while not locked. The interface between the EEC and the end-effector has tabs that slide along guiding surfaces on the tool station until they enter a dedicated slot. This part can be redesigned at will. The important feature is allowing tolerances to slide the end-effectors inside the docking station (as required to engage the EEC).

C. Feet changing

The feet of a humanoid robot have a higher payload as their main purpose is locomotion in various environments. Yet the payload acts mainly in compression and in ankle torque stresses. The feet EEC shall be strengthened accordingly. We describe the changing of a foot that introduces two major challenges compared to arm's end-effectors: (i) balance constraint, and (ii) occlusion of the foot by the robot's body; that is to say, feet shall be engaged and disengaged blindly.

1) *Balancing the robot while changing a foot:* During the motion, the balance is kept using the stabilizer presented in [17]. This stabilizer is based on a linear inverted pendulum model. It accounts for external wrenches from supplementary contacts by adding offsets derived from the applied external wrenches to the CoM and ZMP. When the robot stands on one foot while changing the other, the force applied by the changing foot is considered an external wrench. When possible, to reduce the ankle torques, we use additional arm

contacts (here on the table). It also enlarges the CoM balance region of the robot as in [21]. The wrenches applied by the hands are limited due to a lesser payload for these limbs compared to the feet.

2) *Design of the tool station:* Most of the time part of the robot body occludes the motion of the feet while changing them. Thus changing the feet does not rely on vision. Therefore, we use the feet force sensors to locate precisely the position of the station. The latter is designed to be simple to build and use; of course, other designs are possible. The detached feet are stored close together so that the robot can reach both at a time. Contrarily to arms, the robot can't walk without feet or with one foot! Also, their relative position is known precisely so that the robot can move its leg from one to the other with low error in positioning. Figure 6 shows the approach of the foot station we adopted for the right foot. Initially, the new foot to be equipped is stored on one side (here right) of the foot station while the robot deposits its equipped one on the other (here left) side. Using the ankle force-torque sensor the robot contacts the profile on the right.

Then, the foot slides along the station guide until contacting its front and then left sides (Motion from \textcircled{A} to \textcircled{B}). The relative pose between the station and the robot is estimated by the kinematics of the robot. The following motions account for the estimated pose of the station in particular for its orientation as the robot may not initially be aligned with it. Then the foot slides back against the station until it touches its back. During this motion, the green parts of the station will make contact with the little sphere on the bell of the EEC and unlock it (from \textcircled{B} to \textcircled{C}). Once the EEC is unlocked, the robot will disengage the current foot by twisting its ankle to the right (Rotation around z^+) until contact is detected in the EEC; then lift its ankle without the foot. The robot then moves its ankle above the new foot (from \textcircled{C} to \textcircled{D}). To engage its new foot, the robot lowers its leg and turns it to the left. Then, similarly to how the EEC has been unlocked, it is locked again by sliding the foot backward (from \textcircled{D} to \textcircled{E}). Finally, the robot can move its foot away.

During these motions, keeping contact is ensured using different target wrenches enforced using admittance tasks in the control of the robot's leg. These wrenches ensure non-zero normal forces along the sliding surface to have a precise motion [22]. Motions are generated by a target body velocity along the desired sliding directions. Each motion ends when a threshold contact force is detected. For the rotation when engaging and disengaging the EEC, the motion stops when a threshold torque is detected. When disengaging the foot, controlling the ankle force enforces the removed foot positioning. Another difficulty during this motion lies in the kinematics of the robot: when position \textcircled{D} has been reached, some joints of the robot such as the right knee are close to their range limits. In contrast to arm changing, there is no extra-part on the foot to store the foot in the station. Thus, the design of the foot station must account for different foot sizes. Our foot station can account for a height variation of up to 2 cm. For higher variations, another design is necessary.

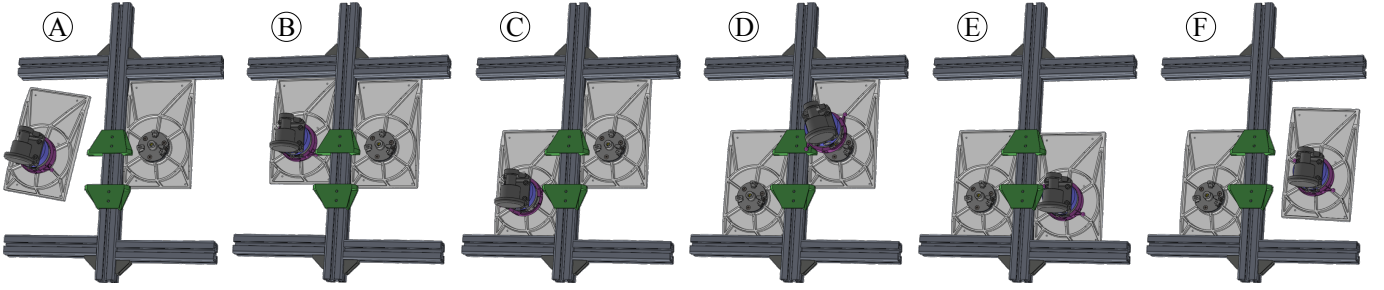


Fig. 6: Top view of the (right) foot docking/storage station (dark gray aluminum profile and the 3D printed green part). The light gray rectangles are the feet of the robot. The one on the right is stored at the foot station while the left one is still attached to the robot (black part is the ankle link of the robot and purple part is the locking bell of the EEC).

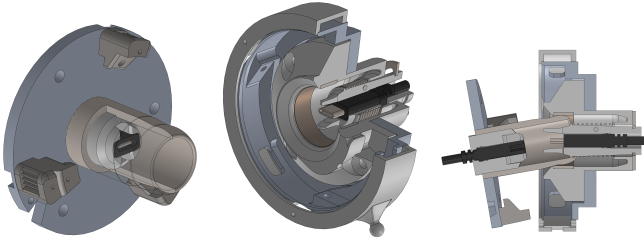


Fig. 7: CAD of the head end-effector changer with USB-C pass-through. From left to right: tool side, robot side and engagement step. On the robot side, the USB-C cable can rotate with respect to the EEC as during the last rotation of the engagement, the cable is already plugged-in.

D. Head changing

The head of a humanoid robot usually carries sensors that require large-bandwidth data transmission (e.g., cameras, LiDARs, etc.). It can also be used for social interactions and could be a sophisticated mechanism embedding several actuators, sensors, or even displays. Thus, for head changes, several specificities are considered.

First, previous devices, if mounted on the head of the humanoid, require different sockets. Until recently, many different connectors existed depending on such devices' brands. This year, the European Parliament (and highly likely other international regulation bodies will follow) imposed USB-C as the standard for all electronic devices to meet sustainability and ecological trends by reducing waste. Thus, we integrate this standard into our head EEC design, shown in Fig 7.

Second, because changing the head implies changing a sensor that is essential for the humanoid's localization, the robot would be 'blind' during the operation. A possible solution is to use an external camera mounted on the environment close to the head tool station or another part of the robot, such as its torso. Such a camera would then communicate with the controller (WiFi) to servo the humanoid to the appropriate replacement head location.

Because there is usually no force-sensing device between the neck and torso, head EEC contact control uses force sensing available at the other end-effectors. For example, those available at the feet, or when kinematically possible, use the arms to perform or assist the head change.

To make a satisfactory head EEC integration into HRP-4, substantial mechanical engineering efforts are needed (some changes would be irreversible). Therefore, we demonstrate the head-changing process, considering the head in its simplest form: a camera. The head EEC used is the same as the one for the hands. The tool station design is similar in shape to the wrist (hand EEC) tool station. Yet, the changing motions are closer to foot-changing behavior, where the locking (resp. unlocking) happens during the releasing (resp. storing) of the end-effector. The head-changing motions are generated by the same task-space controller operating the humanoid, specifying desired translations and rotation at the neck level, inducing whole-body motions (see attached multimedia).

V. DISCUSSION

Our demonstrations, although in a lab setting, revealed the high potential of embedding future humanoid robots with EEC mechanisms. It is the main claim and idea of our paper. There are many possible improvements in the mechanism, the engagement and disengagement processes, and the software.

In a manufacturing industrial context, using EEC is to be compared (in terms of cost, size, flexibility, weight, etc.) to a sophisticated fixed gripper with a dexterity comparable to human hands. Our demonstrations confirmed our claimed advantages: (i) direct control of the end-effector from the robot's software without an extra interface; (ii) robust and repetitive handling of any attached end-effectors; and (iii) their precise use as their relative position to the limb is fixed and known. Furthermore, no internal actuation allows for several benefits: it reduces the size and weight of the EEC and simplifies the hardware integration.

Concerning the outer-locking mechanism, there are many advantages to its design. First, it can be operated by another part of the humanoid (hand change demonstrations) providing reachability. A similar process could be applied to the head and feet. Second, it can be actuated by the tool stations easily; indeed, as for the foot and head, the locking and unlocking can be triggered passively by the interaction between EEC and the tool station. Finally, a human operator can also operate it.

The rationale behind the pin/shaft (Fig. 1c) for engagement does not lie only in having enough relatively large tolerance in positioning and misalignment. In fact, as illustrated by the head changer design (Fig. 7), the center of the EEC would

also serve the purpose of conducting fluid or air pressure in applications that require it. Instead of a USB-C connection, a push-to-connect fluid coupling with automatic shut-off valves could convey fluids without leakage through the EEC. In this case, the shaft is hollowed to integrate commercially available fluid/air connectors; this is part of our future work for applications beyond humanoids (e.g., modular robotics).

As a limitation, since our EEC has been designed for humanoid robots that have kinematics redundancy and various positioning possibilities (floating bases), it is challenging to use it as a docking mechanism in modular robotics or space components. Also, our demonstrations show that in some postures, our humanoid robot is limited in motion range (especially the feet), which could lead to planning complex postures to put or remove a given end-effector. This issue echoes our past recommendations to increase future humanoid motion's range in [1], [4] for other purposes.

In the literature [10], [11], [18], tool-changers are evaluated by repetition of the tool-changing motion with various initial positions and measuring the number of successes and failures. To show the robustness of our design, we also repeated the motion of the EEC but introduced variability by alternating the new end-effector. Due to the limits on the payload of the arms of our humanoid, there were no particular issues when working with these end-effectors. On the other hand, for the feet, one of the parts broke (as expected from the simulation results). After fixing it, we limited ankle torques by imposing extra contacts. Of course, an innovative next design step would undergo more thorough cycle trials to meet industrial norms in robustness and efficiency.

In future work, we will consider having end-effectors placed anywhere in the environment or on the robot. We will also integrate an inner sensing mechanism to assess full engagement and intended disengagement. For now, the system could be unlocked by accident without the robot being aware of it.

VI. CONCLUSION

We devised a novel end-effector changer for humanoid robots. We have listed reasons why usual commercial tool-changers are not suitable and conducted pilot tests with two existing ones. These allowed setting constraints and requirements for humanoid end-effectors (gripper/tools, feet, head) changer design. We proposed a passive changer mechanism and assessed its relevance and benefits in humanoid usage. Our design was prototyped and integrated into our humanoid HRP-4. This led to two major conclusions: (i) the proposed solution operated by another limb of the humanoid is viable and offers a lot of possibilities; (ii) end-effector changers can be integrated into humanoids as they increase versatility while keeping precision and control over the used end-effectors and tools. We will pursue our efforts to improve our design by attempting to evaluate and increase its payload while implementing it in commercial humanoids and animaloids.

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