An Open-Access Passive Modular Tool Changing System for Mobile Manipulation Robots

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***Abstract*— Mobile manipulator robots can benefit from utilizing a range of tools such as: screwdrivers, paintbrushes, hammers, drills, and sensors such thermal cameras. Proprietary tool changing systems exist for stationary robots but we are not aware of one for mobile manipulators. We design and implemented a modular tool changer with three components: robot attachment, tool attachment, and tool housing, designed with the following constrains: low-cost, backlash-free, compact, lightweight, passive, and modular. The tool changer is compatible with many robots and was evaluated with the Fetch robot for 100 repetitions of connecting and releasing the tool, of which 92 were successful. All 8 failures were due to inaccurate position of the robot arm. Changing a tool, from pickup to return, took on average of 16 seconds. This work is part of an ongoing research project on precision irrigation. The design is open-source and freely available at: `https://goo.gl/zetwct`.**

I. INTRODUCTION

One of the main challenges in mobile manipulator robots is providing them access to tools. A mobile manipulator robot must have the ability to firmly grasp tools and manipulate them by applying forces and moments to achieve high level of automation. A recent study by Schmalz Inc., a leading supplier of automation and handling systems, reveals that the automated tool changers not only increase the robot's speed of operation but also perform tool changes that are otherwise extremely tedious to do manually [1].

In order for a mobile manipulator robot to perform diverse tasks in domestic and soft industry environments (i.e., agriculture, hospitals, commerce, etc.) the robot needs to interact with its surroundings, often by using a robotic arm with end-effector. The end-effector can take the form of a gripper or a custom tool designed for a specific task. Designing a single end-effector that is suitable for variety of complex tasks is extremely complicated and often impossible. For example, consider the case of a mobile manipulator robot designated to domestic tasks (Figure 1). The robot may need access to a variety of tools, both passive (e.g., brush, hammer) and actuated (e.g., drill). The robot may also need access to a variety of sensors such as imaging (color, thermal) and tactile. Agriculture robot is another example of mobile manipulator that can make use of the suggested tool changer. Such a robot (e.g., [2]) will need access to variety of passive tools (e.g., shovel, rake), actuated tools (e.g., pruning shears), sensors (e.g., moister sensor, imagery equipment), and combined tools such as Berenstein et al. suggested that combine spraying noozle, rgb camera, and pan-tilt head [3].

Fig. 1: Top: mobile manipulator robot equipped with the tool changer system, and tool housing. Bottom: example tools.

The goal of this work is to design a tool changer device and method for mobile manipulator robots. We propose that the robot will use the tool changer to gain access to a variety of tools and sensors. The tools will be situated on racks, each in its own housing, and the robot will pick up the tool it needs, perform the task, and return the tool to its housing.

In the scope of this work we do not investigate how the robot will find each tool and decide which tool to use, which will be topics for future work. Moreover, we do not study algorithms and methods for accurately aligning the robot with the tool. In this work, we manually specified the desired spatial positions and carefully reset the robot's initial position in order to connect with the tools.

The main contribution of this work is the *design, implementation, and evaluation of a novel tool changer for mobile manipulator robot*. The design we suggest uses male/female truncated cone (Figure 1, 2) to connect the tools to the robot. This backlash-free fastening method enables accurate

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control over the tool. The two-cone design also provides high resistance to applied moments. The tool changer is mostly 3D-printed which contributes to the potential adoption of the concept in other robotic labs and industry. 3D-printing also keeps the tool changer light-weight due to the use plastic (PLA). The constraints that guided us through the design process were for the tool changer to be low-cost, backlash-free, compact, light-weight, passive, and modular.

The paper is organized as follows. Section II discusses related work and the current state of the art. Section III discusses the designed system and its components. Section IV presents the experimental evaluation of the tool changer. Future work and conclusions are discussed in Section V.

II. RELATED WORK

Tool changer technologies (both automated and manual) for Computer Numerical Control (CNC) machines have been quite prevalent in the industry for over three decades [4]. The ability of machines to perform multiple tasks has become the standard in most industries. Manufacturers design their robots to be increasingly flexible, which has led to the development of multiple tool changers within the industrial sector [5]. Compared to industrial machines, the work on tool changers designed specifically for mobile manipulator robots has been limited. Design specifications for the latter are very different from those of standard industrial machines. This discrepancy stems from incompatibility of existing attachment methods between tool changers and mobile manipulator robots and to a lesser extent from weight and torque limitations of some mobile manipulator robots [6].

There have been multiple efforts in advancing tool changing technology in the industrial setting. While manual tool swapping provides an attainable solution to this problem, the speed and accuracy of tool changing required for certain processes can only be efficiently achieved through automation. High speed precision manufacturers require rapid automated tool changing for increased efficiency and lower process cost through the reduction of non-cutting and errors caused by clamping the work piece multiple times [7]. Some processes are very unsafe and thus the introduction of automated tooling can ensure the safety of the machine operators. More so, automatic tool changers can decrease non-cutting time and production costs while increasing productivity [8], [9], [10]. In 2014, Rogelio et al. proposed an Automatic Tool Changer for the 3-axis computer numerically-controlled router machine of the Metals Industry Research and Development Center [11]. This device reduces the duration of tool-change operations, thus enhancing machine productivity.

Clevy et al. present an automated tool changer that exchanges the tip of a micro-gripper with dedicated tools that carry out very specific tasks [12]. Studies have been carried out to tackle the repeatability and precision working-tool positioning micro-instrument tool changers [13]. Tool changers have also been studied in the context of additive manufacturing, particularly for extrusion-based processes [14]. Table I outlines the properties of some of the current leading automated industrial tool changers. In 2017, Tian et al. explore the operational reliability of the tool magazine of an automatic tool changer. The reliability measurement is hinged upon the tool pulling force and is calculated by a stress strength interference model on each individual string [15]. Reliability studies are essential because the tool changer's reliability has a direct impact on the reliability level of the machining center [16]. Studies have been carried out on the rigid body and dynamic simulations have been carried out to improve the structural design and further optimize automated tool changers [17].

TABLE I
Proprietary robot tool changers [19], [20], [6]

Maker	Actuation	Payload [KG]
ATI QC-26	Pneumatic	25
ATI QC-40 with RTL	Pneumatic	50
Schunk SWS-001	Pneumatic	1.4
Schunk SWS-005	Pneumatic	8
Schunk SWS-011	Pneumatic	16
RAD TC-11	Pneumatic	16
Ristec TCRITI-071L	Pneumatic	20
IPRautomation TK-50	Pneumatic	12
Nitta xc-10	Cam	10
Robot System Products TC20-4E	Pneumatic	20

In addition, automated tool changing has been explored in the context of agriculture. The Farmbot Genesis XL, an open source precision agriculture device consisting of a Cartesian coordinate robot farming machine with software, documentation and a farming data repository included. This robot can carry different agricultural tasks using its built in tool changer containing racks with different tools to which it can attach its self [18]. One of the limitations of this tool changer is the nature of the Cartesian robots that allows only 3 degrees of freedom motion and rotation. In addition the device size has to scale with the farm land to allow complete coverage of the Cartesian robot that does the farming. The device we present can attach to any mobile manipulator robot and thus benefit from their seven degree of freedom motion.

In 2011, Gyimothy et al. propose one of the few tool changers designed specifically for mobile manipulator robots [6]. In addition, an experimental evaluation was performed to validate the device's performance characteristics. The study is one of the few attempts to catalogue design and system requirements for automated tool changers targeting mobile manipulator robots. One of the main limitations in Gyimothy's device is the complexity of its manufacturing process. In addition, the tool changer is electro-mechanically actuated.

In contrast, we propose a passive device, actuated purely mechanically that can be coupled with mobile manipulator robots without any additional electronic components. The majority of our tool changer pieces can be made using any standard 3D printer. The benefit of a passive mechanism is its robustness, simplicity to manufacture, maintain and repair, and simplicity of operation.

There have been studies detailing the interfacing of tool changers with various robots. McKinley et al. proposed an automated tool changer implemented on the da Vinci Surgical Research Kit [21]. This tool changer swaps out tools during multi-step supervised autonomous surgical tumor resection. In addition, studies have been done to test the stability and reliability of tool changing racks and automatic tool changers [22]. An automated tool changer was designed for swapping out robot tool tips member mounted on a tool body on a robot arm. This device does not require additional driving power, was described in a source for changing a tool tip member [23].

Tool changers have also been explored in the domain of unmanned robotic platforms. Peters et al. presented a device that has been adapted unto the dexterous arm of the iRobot Warrior, an unmanned robotic platform from iRobot Corporation. The system was designed to allow multiple moving end effectors to share a single capable motor, rather than each end effector having its own motor [24].

III. SYSTEM DESIGN

The tool changer for mobile manipulator robots was designed with the following constrains:

1) *Low-cost*. Manipulator robots require the use of multiple tools to perform tasks. Low-cost design will enable the implementation of the tool changer in the home and soft robot industry,
2) *Backlash free*. Preventing backlash between the robot and the tool provides high accuracy and tool position repetition. Backlash-free design will also contribute to future sensors attachments,
3) *Compact and light-weight*. Compact and light-weight design of the tool changer will enable fitting the tool changer to a variety of small to medium mobile manipulator robots, such as the Toyota HSR, the Fetch, and the ABB YUMI,
4) *Passive mechanism*. The passive design (i.e., no power or data required) of the tool changer contributes to the reliability and robustness of the robot-tool connection mechanism,
5) *Modular design*. Modular design will provide the option for different robots to interact with large set of tools with the need for unique tool adjustment.

The tool changer designed in this work is assembled from three main components: robot component (Section III-B, Figure 2b), tool component (Section III-A, Figure 2a), and the tool housing (Section III-C, Figure 2c). The design objective of the tool changer focused on providing a low-cost passive mechanism that enables work within strict financial constraints. To that end, the design minimizes the need of custom machined components and instead mainly utilizes additively manufactured components from affordable 3D printers manufactured using PLA. The dowel pins and washers are custom machined aluminum pieces; the springs and the bearings are standard off-the-shelf components. The rest of the assembly is 3D-printed.

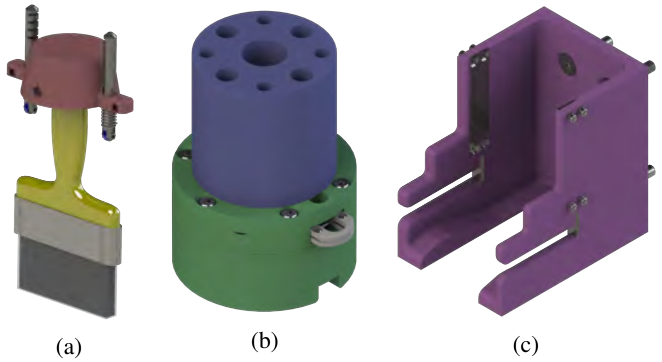
(a) (b) (c)

Fig. 2: Three tool changer components. (a) The modular base component is based on truncated male cone with two flanges on its sides and a pair of spring-compressed dowel pins. (b) The robot component is the female truncated cone that connects the the tool component. The top (blue) part is an adapter for the Fetch robot which was used to evaluate the tool changer. (c) The tool housing serves as storage for each tool and provides the structural constraint to allow passive connection of the tool changer.

A. Tool component

The tool component is a 3D-printed male truncated cone with two rectangular flanges, extending on each of its adjacent sides. The tool component was 3D-printed with PLA using Ultimaker printers with 0.4mm nozzle. The tool component is constrained via a conical kinematic coupling between the interchangeable tool and the robot component's female cone. The tool component contains two spring-retracted dowel pins (Figures 2a, 3). These pins are used to mount the tool to the robot component and by compressing the springs maintain pressured contact between the tool and the robot component, which prevents backlash. For the locking mechanism to work, the slot must face the middle of the tool component (and facing each other). We constrained the rotation (around the z-axis) of the dowel pin by adding a slot on the pin and a tab on the tool component (Figure 3). The bottom part of the dowel pin is equipped with a ball bearing for smooth compression of the spring while the bearing is rolling on the tool housing incline plane (Section III-C, Figure 5).

The tool component should be positioned accurately in the tool housing. For that, we designed several elements that constrain the tool component to the tool housing (Figure 3). A conical hole was created to align with the conical rod described in Section III-C and together constrain the y-axis and z-axis. Constraining the x-axis is achieved by adding magnets to the tool component side flange and magnetizable steel on the tool housing.

B. Robot component

The robot component is assembled from four main parts: robot adapter, cap, locking plate, and female truncated cone (Figures 2b, 4) all 3D-printed with PLA using Ultimaker printers with 0.4mm nozzle. The four parts are connected with bolts and nuts, for easy maintenance and repairs.

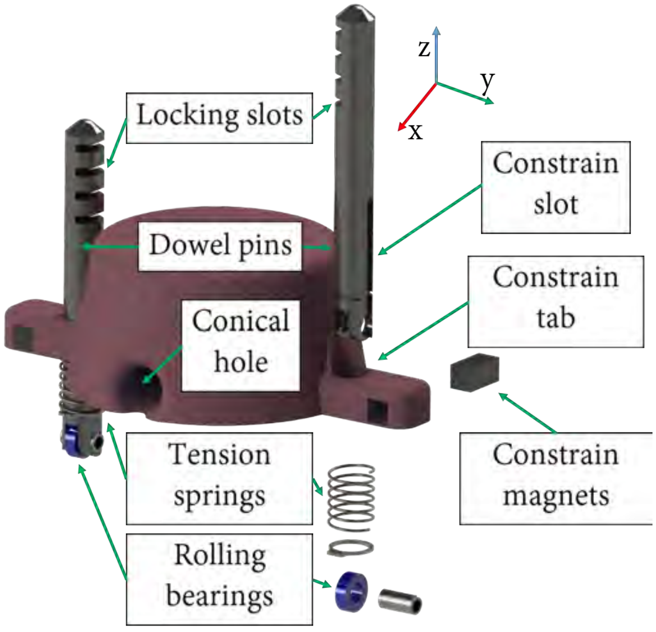

Fig. 3: The tool component was designed to serve as the base to which a variety of tools can connect. The bottom edge of the tool component remains flat and open to installed tools and sensors. The right side of the tool component is shown here in exploded view of the dowel pin, and the left side is assembled.

The robot adapter is the part that connects the robot to the robot component. The robot adapter shown in Figure 4 was designed specifically for the Fetch robot [25]. However the robot adapter can be modified for attachment to any desired robot. The cap has two main roles: to connect the robot adapter to the robot component and to secure the spring loaded blades in the locking plate.

The locking plate serves as housing for the dowel pins locking mechanism. The two locking blades are interconnected with a spring that forces them out of the locking plate. An edge on the locking plate and wings of the locking blade's middle plate constrain the locking blade inside the locking plate.

The female truncated cone is opposite to the tool component male cone and is designed to interact with the latter. On either side of the cone there is a through hole that continues through the locking plate and the cap. This hole allow the dowel pins to pass through and lock using the locking blades.

C. Tool housing

The tool housing (Figures 2c, 5) serves as a rack to hold the tool component when the tool is not in use by the robot. The cage-like structure constrains the tool component in a fixed position and allows it to compress and decompress the locking blades of the robot component. The tool housing has a guiding groove on each side that supports the flanges of the tool component and constrain it on the z-axis.

The tool component is constrained along all three axes once placed in the tool housing. Two magnets attached to the flanges of the tool component maintain contact with magnetizable carbon steel pieces lining the end of the guiding grooves on the tool housing. This connection constrains motion in the x-axis along the tool housing. The magnets have a maximum pull force of 5[N]. A conical rod extends from the back wall of the tool housing and connects with the tool component's conical hole to constrain the tool component on the y-axis and z-axis. The tool housing has incline planes on each side (Figure 5) to compress the dowel pins while the tool component leaves the housing and to allow smooth decompression of the dowel pins when the tool component return.

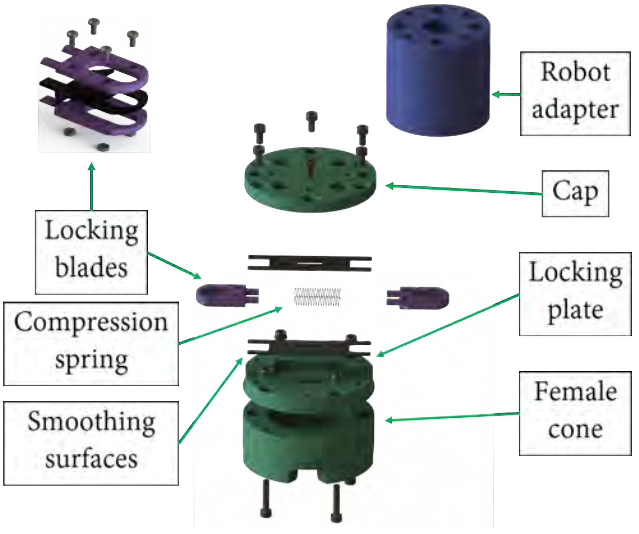

Fig. 4: The robot component is mounted to the robotic arm and is designed to connect to the tool component, cone and locking blades. The outer diameter of the current design is 80mm. The robot component can be mounted to a variety of robots by redesigning the robot adapter (blue part at the top right).

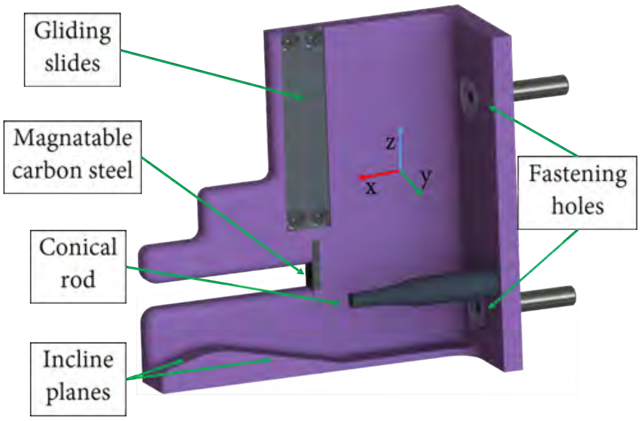

Fig. 5: The tool housing shown in here is cross-sectional view of the symmetrical tool housing.

D. Coupling the robot and the tool components

The process of coupling the tool and robot components requires that the male and female cones connect and the

TABLE II
Loading experiments to characterize optimal incline angle for truncated cone on both the robot and tool components. Samples pre-loaded at 49[N] (5Kg).

Angle [°]	Average Load [N]	Standard Deviation
2	69.1	6.5
5	33.7	5.2
10	28.4	7.5

dowel pins be securely locked. This requires the following steps (Figure 6):

1) *Step 1*, bringing the robot component into the tool housing and positioning it above the tool component. At this point the locking blades are compressed and retracted, and the dowel pins are clear to pass through.
2) *Step 2*, lowering the robot component toward the tool component until the male and female cones are firmly connected. At this point the dowel pins are inside the robot component through the holes.
3) *Step 3a*, exiting the tool housing. At the top of the tool housing incline planes the dowel pins are at maximum compression. The locking blades remains retracted by the tool housing.
4) *Step 3b*, exiting and leaving the tool housing. At this point the locking blades are released from the tool housing and lock the compressed dowel pins causing constant positive pressure between the robot and the tool components.

Decoupling the tool component from the robot component is performed by reversing the coupling procedure.

The connection of the tool component's male cone and the robot component's female cone creates a Hertzian force that might exceed the robot payload, which can cause failure for the cones to disconnect. The Hertzian force depends on the angles of the cones and their diameter (through their contact surface area). Based on the design constrains (e.g., providing space for the dowel pins and maximize the tool component base area surface) we define the diameters of the cones and evaluated the Hertzian forces with different cone angles.

To avoid exceeding the robot payload we measured the Hertzian force developed with three pairs of cones in different angles (2°, 5°, and 10°). We connected the cones with 49[N] and measured the force needed for disconnection. The disconnection forces of the cones are summarized in Table II. Based on Table II and the desire to generalize the design we choose 10° cone design.

IV. EXPERIMENTS AND EVALUATION

The goal of the experiment was to evaluate the tool changer mechanics while using a commercial mobile manipulator robot. Preliminary experiments of connecting and disconnecting the tool changer by hand (human hand imitating the robotic arm) were conducted to make sure the design of the device was valid. However, robotic manipulators lack the subtle senses of humans and evaluating the interaction of a real manipulator robot was essential.

A. Experiment setup

The evaluation process was conducted using the Fetch mobile manipulator robot [25]. The tool housing was mounted vertically, 90cm above ground, to a table leg using aluminum 80/20 beam. We removed the factory gripper and equipped the Fetch with the tool changer using a specifically designed adapter (Figure 2b). The robot was positioned in front of the tool housing (approx 60cm) to allow the Fetch to change tools without moving its base (Figure 2c).

Connecting and disconnecting tools requires that the robotic arm travels between a specific set of spatial positions as illustrated in Figure 8. To connect to a tool the robot preforms the following procedure (alphabetic positions refer to Figure 8):

1) *Position a*. Starting point of the robotic arm. Arbitrary position of the arm before engaging with the tool changer.
2) *Position b*. The robot approaches the tool housing while rotating the robot component over the z-axis.
3) *Position c*. While moving forward $(+x)$, the robot component rotates over the z-axis. This rotation provide smooth compression of the spring-loaded blades. At the end of this move the robot component is directly above the tool component.
4) *Position d*. The robot moves down $(-z)$ engaging with the tool component. At the end of this motion, the robot and the tool component cones are connected.
5) *Position e*. The robot moves back $(-x)$. While moving, the dowel pins are compressed by the tool housing incline planes and enter the robot component's designated holes. At the top of the incline plane, the spring loaded blades are released from the tool housing and lock the dowel pins.
6) *Position f*. Stepping back from the tool housing with the tool component firmly connected.

The tool releasing procedure is opposite to the connection procedure, with the only difference that in the releasing procedure there is no rotation around the z-axis to prevent collision with the conical rod.

Prior to the experiment, the robot was manually positioned in the starting position of the tool-connecting procedure and we performed two dry runs of the connecting and releasing procedures; first without the tool housing, and second inside the tool housing but without the tool component. This was done to ensure that the robot was aligned with the tool housing and the desired motions are followed.

Interacting with the robot was based on ROS with Moveit! as the motion planner of the robotic arm.

B. Experimental evaluation

The experiment consisted of 100 repetitions of the robot connecting with the tool and releasing it back to the tool housing. Since automatic guidance of the robotic arm toward the tool component is outside the scope of this work, a human

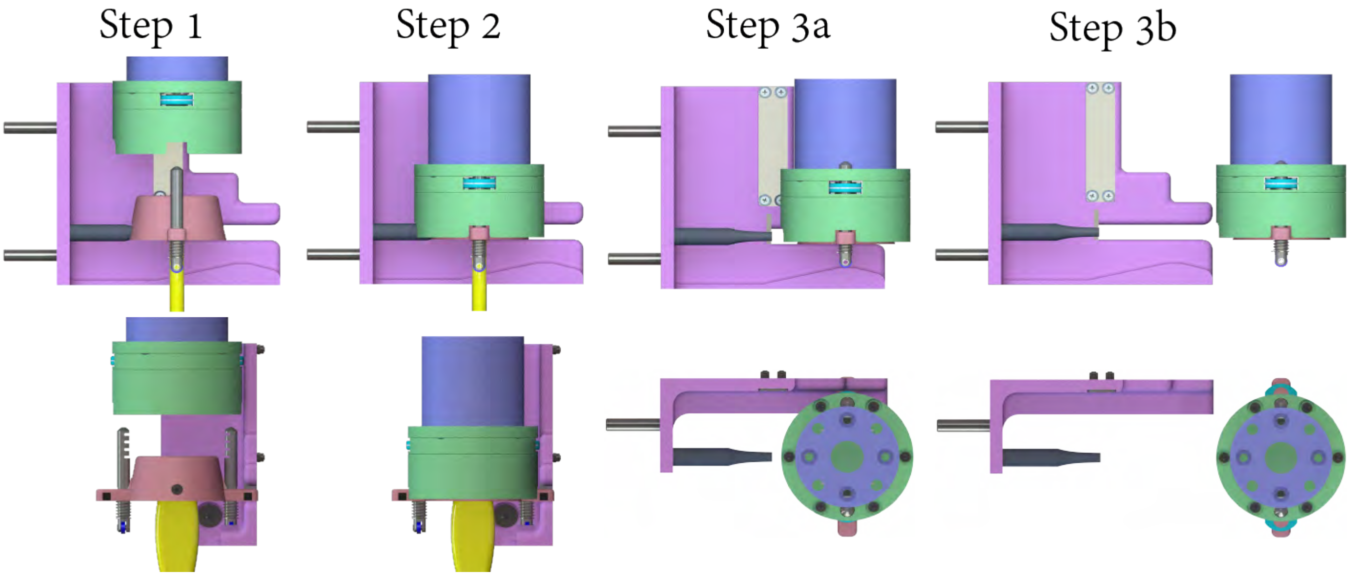

Fig. 6: Steps needed towards successful connection of the robot and tool components. The top images are side view, the two lower left are front view and the two lower right are top view. For better visualization, the tool housing is presented as cross-sectional view.

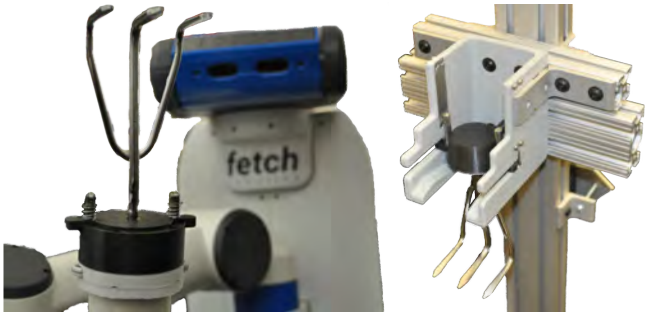
(a) (b)

Fig. 7: Fetch mobile manipulator robot with the tool changer installed. (a) Fetch robot equipped with the tool changer after connecting to a small, carbon steel, garden cultivator. (b) The tool changer housing mounted to a table leg using 20/80 aluminum beam. The tool housing was installed 90cm above ground.

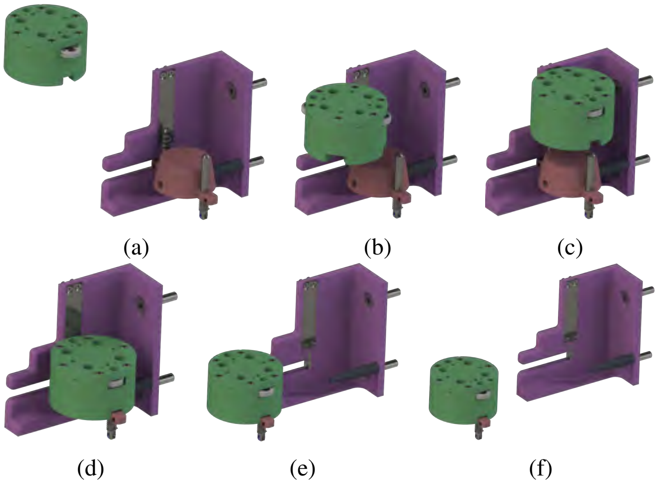

Fig. 8: Six-step tool connection. For better visualization, the tool housing is presented as cross-sectional view.

operator monitored the drift position of the robot base and performed corrections. The corrections were applied solely to the robot base without intervention in the robotic arm positions.

The performance measure of the experiment was the successful connecting and releasing of the tool changer and the post-experiment evaluation of the parts.

The experiment resulted in 92/100 successful connection and releasing of the tool. Examining the results reveals that failures occur either due to inaccurate position of the robotic arm or when the robot arm motion planner changes orientations. Since robot positioning was hard-coded, the timing of each tool picking was constant at 16 seconds.

V. CONCLUSIONS AND FUTURE WORK

Designing, building, and experimenting with the tool changer suggest that the tool housing in its current design does not provide the support needed for contracting the spring loaded blades. We might overcome this by adding support to the tool housing side panels (as we did in Figure 7b). Another option is to fabricate the tool housing from aluminum.

Conducting experiments with the Fetch robot revealed considerable error in robot position, both arm and base. We will explore a tool calibration using cameras to allow accurate positioning of the robot arm within the tool housing. We plan to add visual cues around the tool housing. This will assist the robot localization process which will increase the accuracy and repeatability of the robot (both arm and base).

Another path for future work will focus on advancing the tool component capabilities. We plan to add data (USB) and power (12v) connections between the tool and the robot. This will enable adding sensors such as USB cameras, electrical actuating components such as different robot grippers, and tools that require power (e.g., home drill, vacuum cleaner). We also plan to design a generic tool component with USB connector and fast mounting brackets to allow industrial robots to attach off-the-shelf USB-based tools.

Within the scope of the RAPID project (`rapid.berkeley.edu`) we plan to implement this work on a stationary two arm robot (ABB YUMI) were robot task will be to grow plants in similarly to human. The robot will have access to the same tool set the human does, and in addition variety of sensors (moister, imagery). The goal of this work will be to explore the implementation of the tool changer and to develop and implement state-of-the-art robot learning algorithms specifically for the agricultural domain based on the human demontrations (LfD).

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