A Robot Factors Approach to Designing Modular Hardware

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Abstract— **Robots are increasingly being called on to operate in settings and on tasks originally designed for humans, or where humans are also expected to work. Accordingly, the hardware and tools to be packaged, operated, or maintained are typically designed for use by humans, not robots. Robot autonomy in such cases can be expedited by a "robot factors" approach to the design of hardware, analogous to ergonomics for humans, taking typical current robot capabilities into account during the design process. In this paper, we present two case studies of redesigning mission-critical hardware in space habitats to facilitate autonomous robot operation. In both cases, hardware that previously required dexterous bi-manual manipulation is redesigned such that the entire maintenance task can be completed by a single robotic arm with a standard parallel jaw gripper. We demonstrate successful autonomous replacement of modules in the two hardware systems, and characterize how orientation and compliance of a grasp helps compensate for positioning errors. Based on our findings, we identify several key design strategies that underpin the robot factors approach to designing robot-friendly hardware, including consolidating compound actions into simpler mechanisms, constraining required motions to a single axis, and introducing mechanical compliance to mitigate the effects of pose uncertainties.**

I. INTRODUCTION

Robots are widely used in manufacturing, warehouse management, and other domains where their environment can be precisely engineered and controlled to suit them, but they are as yet unable to achieve similar performance in human-centric settings. Much effort in robotics research is aimed at improving perception, manipulation, and so on, with the aim of bringing robot capabilities closer to those of humans. The opposite approach is to design elements of an environment, in which robots are expected to operate, with robots in mind—bringing the world to match current robot capabilities [1]–[4]. This approach has been given names such as "robot factors" and "robot ergonomics", by analogy to the field of human factors/ergonomics.

Just as human factors is generally concerned with how hardware can be designed to facilitate human operation, the aim of the "robot factors" approach is to design hardware that facilitates robot manipulation. The goal is to promote autonomy by redesigning mechanical interfaces, devices, and assemblies such that they can be easily manipulated by readily-available robot platforms and end effectors. In other words, by developing slightly more sophisticated devices, we may require considerably less sophisticated robots for reliable manipulation of them [5], [6]. Not only can this approach make existing robot operations more reliable, it can also enable robots to perform tasks that they would not be otherwise capable of performing.

In this paper we apply a robot factors approach to the design of an interface for replaceable modules in a larger system. We consider, as concrete case studies, two examples of routine maintenance tasks relevant to the setting of a space habitat. One reason for considering this context is that in conventional settings, particularly in the shorter term, there is a limit to how much we can expect to be able to dictate the details of the environments and hardware that robots may be called on to deal with; by contrast, in more exotic cases being designed from scratch, more opportunity may exist to determine such details afresh.

The first case study concerns the modular power system of NASA's AMPS project [7]; the second focuses on the water filtration component of an environmental control and life support system (ECLSS). In both cases, replacement of a modular unit currently requires a coordinated sequence of bi-manual motions, dexterity, and precise motor control beyond the capability of most commercially available mobile robots. For each case, we first present the existing hardware, and highlight specific obstacles to robotic operation. We then discuss design changes we make when reconsidering the task from a robot factors perspective. Both case studies represent examples of interfaces that would be useful for broader classes of applications, and could be adapted to a wider range of modular systems. The execution of each task is demonstrated using a UR5e robot arm equipped with a traditional two-finger parallel gripper, showing that the hardware is operable without more sophisticated systems. A concluding discussion offers general mechanical design principles for future hardware design.

II. RELATED WORK

The field of human factors has, as one of its goals, the development of design strategies for improving usability of objects for broader classes of human users. For instance, consideration of those with a variety of disabilities (e.g., hearing, sight, and motor impairments) results in products with accessibility features (such as text-to-speech functionalities, larger visual cues, ergonomic handles [8]) that improve the experience for these users.

The robot factors approach can be seen as a generalization of these goals, by including robots in the pool of users. The desired result is tools, interfaces, and devices that are easy

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(A) **Removal**

(B) **Installation**

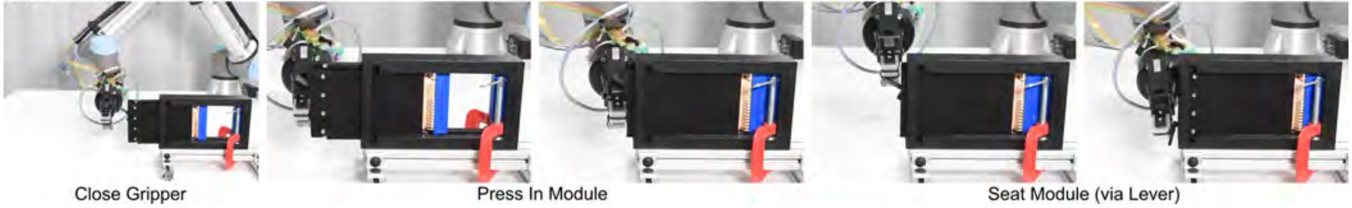

Fig. 1. Removal and installation of a power module is performed by a single 6-DoF robot arm. The simple mechanical advantage afforded by the longer lever reduces the torque requirement to fall within the robot's specified range (details given in text).

to use by both humans and robots.[1]

Three ways to improve robot performance in human environments are (1) modifying the environment in which the robot operates, (2) modifying the robot itself, or (3) modifying the hardware that the robot manipulates.

(1) Environments can be designed or modified to suit robot capabilities in three different contexts: (a) Cases where humans are explicitly excluded (e.g., certain factories and warehouses). (b) "Robot-inclusive environments" [9], where a space is designed to better support robot execution of a given task. Examples include vertical gardens that integrate modular track systems that facilitate robot locomotion, design guidelines for false ceilings and concealed infrastructure that facilitate robot locomotion for utility inspections, and guidelines for hospitality facilities [10]–[12]. (c) "Robot ergonomics" [4], where architectural environmental elements (e.g., wall and floor surfaces, furniture selection, lighting schemes) are designed to support both human and robot workers. The principles of "Universal Design" (a design philosophy aimed at accommodating elderly or disabled users) have been extended to accommodate robots as well, and guidelines have been published suggesting general home modifications to support robot co-inhabitants [13].

As compared to creating or modifying environments to enhance robot operations, robot factors is more concerned with designing devices, tools, and interfaces that facilitate robot manipulation.

(2) Much work in the field of robotic manipulation focuses on building robotic hardware and software capable of dealing with the large uncertainty encountered in real-world applications. The typical approach centers on advancing high quality sensing and perception, robust control, and task planning algorithms that can handle large variability in task requirements [14]–[16]. An alternative approach is to develop end effectors with a passive ability to handle uncertainty in objects and the environment; this path has led to many successful gripper and hand designs [17]–[20].

Another research area that has developed useful designs and principles for this purpose is that of modular robotics, particularly self-reconfigurable modular robots, where mechanical, electrical, and other connections need to be made reliably, autonomously, and frequently [6], [21], [22]. An alternative approach in modular robotics (sometimes known as material-robot systems) deals specifically with robots and building materials that have been co-designed to interface with each other [23]. While this approach can be effective for systems where all components are designed at the same time, robot factors assumes having no direct control over robot design, and thus seeks to develop devices that can be easily operated by generic manipulators.

(3) Designing hardware to allow manipulation by robots [2], as well as by humans [1], [2], [24], is the central theme of robot factors. Prior work has demonstrated improved gripper reliability when ordinary household tools are outfitted with a custom universal attachment [2]. Other work has argued that designing hardware that is "robot friendly" will be critical for future remote systems to be capable of autonomous self-repair [25].

The above examples illustrate the value of modifying the designs of systems or devices with which robots interact. However, so far there have been limited efforts to establish general principles for designing for robots.

III. CASE STUDY 1: POWER MODULE

We first consider module replacement for a power system proposed by NASA for use in future space vehicles [7].

A. *Existing hardware*

NASA's Advanced Modular Power Systems (AMPS) project seeks to standardize future space power system architectures by using a modular approach. All modules conform

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[1] Here we use the term "robot factors" as it has been used in prior literature, to refer to an approach that expands the pool of users to include both humans and robots. A more literal use of the term would consider only robots in the user pool, which would be relevant for scenarios where objects are intended for robot manipulation only. A distinction between "robot factors" in the latter sense, vs. a term like "user factors" to encompass both groups, may be useful for future work in this area.

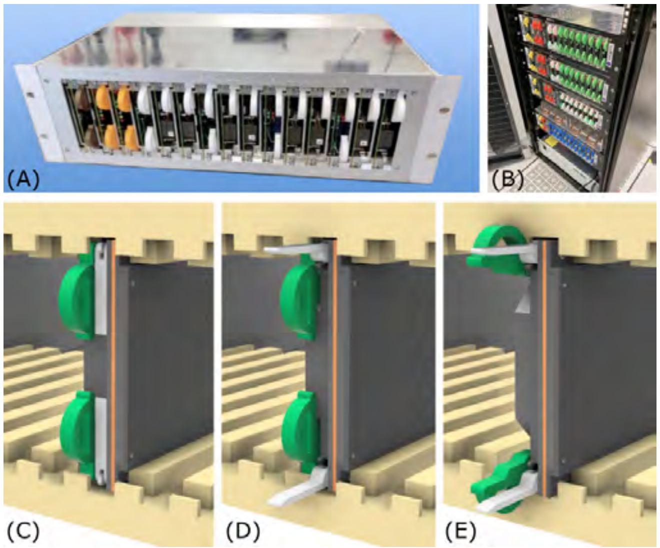

Fig. 2. Existing AMPS prototype. (A) Modules are installed in an aluminum chassis. (B) Multiple chassis are contained in a cabinet. (C) Removing a module requires first unlocking the wedgelocks (white) by pivoting them 90° from their pictured position. The injector handles (green) obstruct access in a way that precludes grasping them with an ordinary pinch gripper. (D) Once wedgelocks are open, (E) the injector handles must be operated simultaneously, a bi-manual operation that requires considerable force (and typically bracing against the chassis for leverage). Note that in the presence of gravity, wedgelocks (white) must be actively held horizontal while sliding the module out of the chassis, or they will fall, causing the module to lock against the chassis. (Images in (A–B) reproduced from [7]).

to a standardized form factor, but provide different functions (e.g., Housekeeping Module, Bi-Directional Converter, Load Switchgear Module, Portable Equipment Charging). These modules are built around the Positronic PCIH47 connector, which features 47 pins, evenly split between large power contacts and smaller signal contacts.

Module replacement with the current AMPS design may not be possible with any of NASA's currently available robots, and can even be challenging for human hands (especially if gloved). Replacing a module requires two distinct sets of motions in a constrained space; insertion/ejection, and wedge locking/unlocking (Fig. 2C-E). Insertion/ejection is a bi-manual operation that requires forces on the order of hundreds of Newtons. Wedge locking/unlocking requires dexterous manipulation (and in some cases a fingernail or small screwdriver) in order to access the locking levers.

B. Revised design

The primary modifications were aimed at reducing both the dexterity and the number of simultaneous actions (such that the task can be completed with a single arm) required to replace a module. The redesigned power module uses a gear assembly to coordinate different types of motion output using a single input, supplied by the robot pulling a lever along a 120° stroke. Fig. 3D–F shows a cutaway view of the internal mechanism.

For insertion, the first 90° of the stroke of the lever (light blue) causes the injectors (green) to press against tabs in the chassis (Fig. 3C, yellow), seating the 47-pin connector at the rear of the module into the corresponding connector attached to the chassis (Fig. 3D–E). The remaining 30° engages wedge-locks by pivoting an eccentric cam (dark blue) that presses a follower (white) into the trapezoidal wedgelock (black), thereby tightening the wedgelock against the chassis and locking the module into place (Fig. 3F). For ejection, these steps are reversed.

Other design features include the lever handle itself, which provides a single point of contact between the robot and the consolidated mechanism. The handle was designed to be long enough to reduce the peak force required of the robot to perform the operation, while not being so long as to extend beyond the chassis when closed. Careful consideration was given to ensure that the handle could be grasped in both the open and closed positions. In the open (unlocked) position, the handle can be approached from either the front or the side. The lever handle is only in its open (or raised) position during insertion or removal. In the closed position, the lever is vertical and does not project out beyond the face of the chassis; the handle overhangs the edge of the module, providing a feature for the gripper to grab from underneath. There is sufficient clearance around the lever handle for the cabinet door to close, protecting the modules inside.

Two other key modifications enable smooth robotic installation and removal of the AMPS power module. First, the PCB layer was moved in order to align the module's connector with the channel in the chassis. Previously the injectors pushed the module into the connector from two off-center points of contact, while the new version allows the module to be pushed symmetrically from four points of contact (Fig. 3B, green), increasing reliability. Second, the chassis itself was also modified to have filleted edges around each slot opening to guide the module into position.

The mass of a prototyped AMPS module following the original design is 160 g. The mass of the revised module is 184 g.

Other design features that could aid robot operation, but were not implemented here, include compliant or textured grips for the handle (see discussion of compliance in the next case study), and different colors applied to front/back faces of the handle to help computer vision algorithms to determine the state of the device at a glance.

C. Validation

To validate the above modifications to the AMPS power module, we show that the functionality is identical to the original design (i.e., electrical connections are made), and demonstrate autonomous operation of the new design using a typical robot manipulation system. These validation tests show that applying a robot-factors approach to the design of the module turns a dexterous, bi-manual task into a simple, single-handed task.

First, we verified that the newly developed prototype was able to seat the connector as deeply as with the previous versions of the module. The AMPS modules feature verification pins of three different lengths, used to ensure the module is fully seated. For testing and validation, an LED

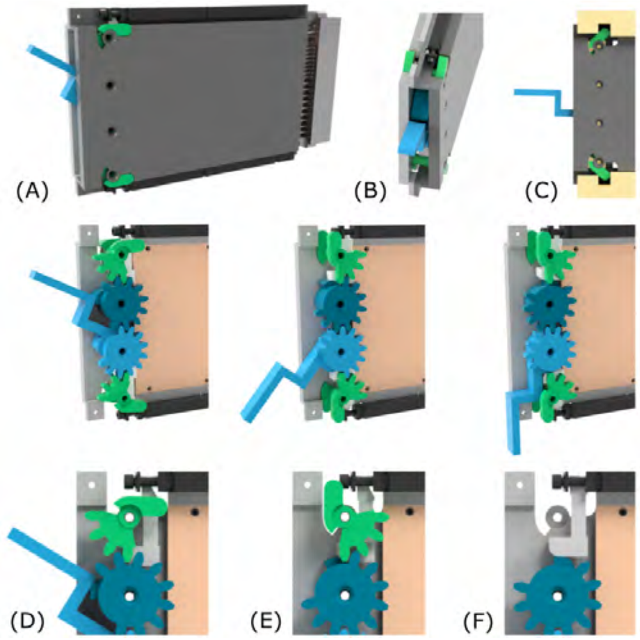

Fig. 3. (A) The revised design for the AMPS module features a single lever (light blue) as the interface for the robot. (B) Centering the PCB allows for the module to be pushed by 4 contacts (green) instead of 2. (C) A cutaway side view of the module midway through insertion into the chassis (yellow). (D–F) A cutaway view showing the internal mechanism of the redesigned AMPS module. (D) The insertion procedure begins with the lever upright. (E) The first 90°of the lever stroke pivots the injector/ejectors (green). (F) The remaining 30°pivots an eccentric cam (dark blue), raising a follower (white) to engage the wedge-lock (black). (Springs, track and green injector/ejector hidden for visibility).

was connected to the shortest of the pin lengths, so that lighting up indicates that the module is fully seated. This lets us visually verify that for both the old design and our modified design, the module is fully seated after insertion.

From here, we demonstrate autonomous replacement of our modified module design using a standard 6-DoF manipulator (UR5e) and parallel jaw gripper (Robotiq 2F85 gripper), as shown in Fig. 1 and the Supplementary Video. Using the arm's built-in six-axis force/torque sensor in the wrist, we measured the maximum forces on the module during insertion and removal. While manipulating the lever to eject the module, the peak force measured was ∼50 N. The peak force measured while inserting the module was ∼100 N. If the robot were to seat the module without any levers, the force required would quickly exceed the force limits based on the connector's rated forces (22 N per contact for each of the 47 power contacts, resulting in 1034 N for the whole connector). Additionally, while operating the short lever arms of the injectors on the original module design would also exceed the abilities of many robots, the force requirements for the redesigned module fall well within the range of commonly-used co-bots like the UR5e. The full sequence (both removal and installation) took 112 seconds.

In additional tests, the module replacement task was conducted using a UR3 robot and a 3D-printed gripper, supporting the idea that the approach is not limited to specific robots or grippers. The full replacement sequence (ejecting the module, setting it down, picking it up, and then installing it) in this case took approximately 4 minutes. The robot was able to successfully perform the full replacement sequence 10/10 times.

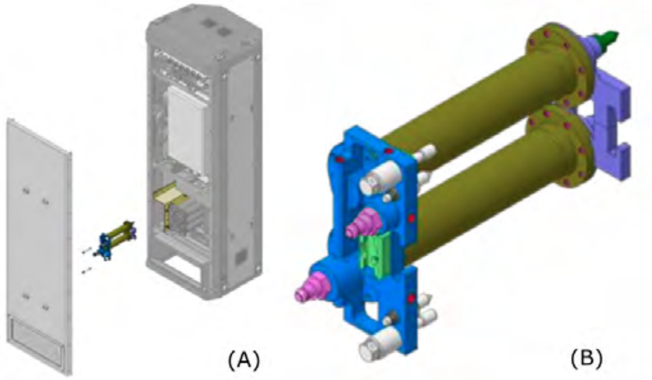

Fig. 4. (A) The location of the filter module within the UTAS/Collins ECLSS unit. (B) Before removing the filter module, captive fasteners (white) must be loosened and hoses must be disconnected from their couplings (magenta). Figures used with permission from Collins Aerospace; © 2022 Collins Aerospace.

IV. CASE STUDY 2: FILTER MODULE

The design for the modified AMPS module interface can be adapted to other modular systems. Doing so provides a single consistent operation for robots to replace units across multiple contexts. In this section we discuss replacement of a water filter module like those used in environmental control and life support systems (ECLSS).

A. *Existing hardware*

United Technology Aerospace Systems (UTAS / Collins) manufactures ECLSS units for use in NASA and ISS missions (Fig. 4). ECLSS units contain water filters, which must be replaced as a matter of routine maintenance (as with AMPS, the modules are enclosed in a cabinet). In order to replace a filter, two hoses must be disconnected from the front of the filter module. In the current UTAS/Collins design, these connectors are Parker quick disconnects, which require retracting a sleeve on the connector while simultaneously pulling the coupling apart (a dexterous maneuver). Next, two captive fasteners must be loosened on the front of the filter module to unmount it. Finally, the module is slid along a linear guide rail until it is free of the chassis. Inserting a new module requires performing the above sequence in the opposite order, including retrieving the loose hoses and maneuvering them to the proper position.

With this modular system, several key design choices, while perfectly reasonable for human operation, result in manipulation requirements that are nearly impossible for robots to perform. Removing the quick disconnects requires simultaneously retracting a collar while pulling a hose in the opposite direction, which is an in-hand manipulation that can be difficult even for human operators. Furthermore, the captive fasteners require a hex wrench to operate.

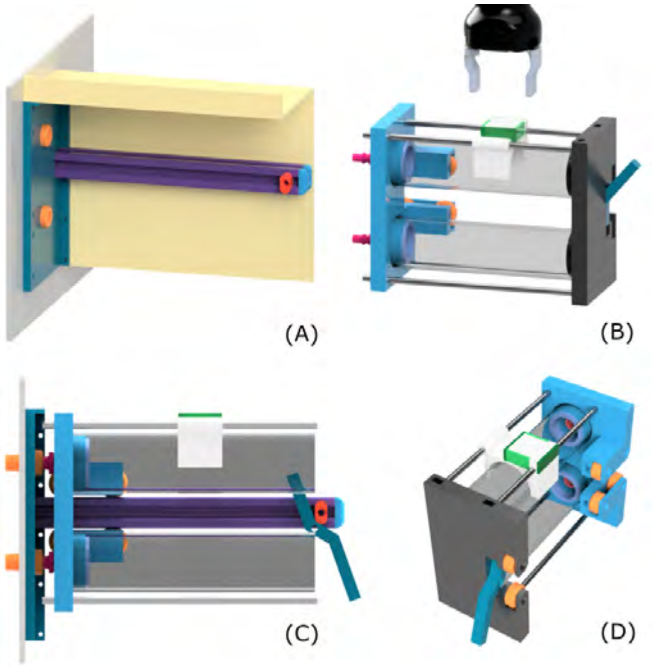

Fig. 5. An ECLSS unit (A) receives the filter module (B). (C) The front panel (black) is removed to show the lever (dark blue) engaged against the protrusion (red) attached to the rail (purple). (D) An alternate view of the filter module highlights the 2 V-wheels (orange) in the front and the 4 in the back, which are needed to support the module when it is only halfway inserted.

B. Revised design

As with the previous case study, a primary modification was to use a lever handle (Fig. 5B, dark blue) as a consolidated interface between the manipulator and the device. A protrusion (Fig. 5A, red) was installed on the rail (Fig. 5A, purple) in order to provide resistance against which the load arm of the lever presses (Fig. 5C). The protrusion is positioned in order to affect the angle of the lever stroke at which the peak coupling force is incurred.

The hose connectors were moved from the front of the filter unit to the back, and replaced with push-pull connectors that can be engaged and disengaged simply with a sufficient amount of axial force. This is achieved by taking Parker quick disconnects, and mounting them such that their collars are mechanically coupled to the ECLSS unit housing. Therefore, when the module is pulled away, the female connectors travel with it for a few mm, thereby retracting their collars and releasing the male connectors. This change enables the insertion force to be provided by the lever arm to couple the connectors, removing the need to connect/disconnect hoses as an extra step. Furthermore, the captive fasteners were eliminated entirely, as the combination of the forces from the push-pull connectors as well as the lever arm against the protrusion is sufficient to keep the module locked in place in the chassis.

To facilitate insertion of the module, rollers were installed to guide the module onto the rail, and a handle (Fig. 5B, white) was added to the top of the module to provide the robot with a dedicated grasp point. The handle was designed with two parallel sets of faces (shown in Fig. 5 as light green and dark green) for easy grasping with standard parallel jaw grippers. The handle was located directly above the center of mass of the empty module to minimize torques due to gravity during manipulation. At the rear of the module, two sets of rollers were installed (Fig. 5, orange) such that the module remains horizontal while halfway inserted into the ECLSS unit. This is critical to ensure a single robot arm can release the module after insertion and re-grasp to finish the task.

The mass of the revised filter module is 723 g (without water). The mass of the original filter module is estimated to be around 600 g. While some mass is added in the revised design (such as roller wheels and a lever), other elements such as captive fasteners are removed. Additionally, the redesign eliminates the need for the lengths of hose connecting the front of the module to fixtures in the back of the ECLSS unit, which would permit further mass reduction to the unit and eliminate free elements that could tangle or snag.

C. Validation

The sequence for removing and replacing a filter module was demonstrated with the UR5e robot arm equipped with a Robotiq Hand-E gripper (see Figure 6 and Supplementary Video). Successful installation of the module was confirmed by circulating water through it, without leakage.

We next explored the effects of angular misalignment, grasp compliance, and grasp orientation on insertion of the module. Uncertainty in the robot's perception, control, and actuation systems during module insertion can result in catastrophic failures in multiple ways: (1) misaligned roller/track interface prevents insertion, (2) misaligned insertion axis results in large off-axes forces applied to the module (exceeding robot limits or potentially damaging the module or housing). To evaluate these effects, we performed a series of insertion tasks with varying insertion angles (up to 6°) to simulate errors in estimating the orientation of the chassis, as shown in Fig. 7A. The resulting forces applied to the module were measured using the force/torque sensor in the robot's wrist. We tested both stable grasp configurations that the handle allows (in-plane with the insertion axis, and orthogonal to the plane, see Fig. 7B), both with a rigid handle and with a compliant handle with neoprene foam (6 mm thickness) on all sides. For these tests, the arm's maximum end effector force was set to 150 N (default).

The results of these tests on angular deviation are shown in Fig. 7C. As expected, the forces applied to the module during insertions are large when using a rigid handle (at best 38 N), while a compliant handle incurs much lower forces (at best 5 N). For both handles, grasps oriented in the plane of motion failed altogether at angles larger than 4° deflection due to the force limits in the arm, while grasps orthogonal to the plane of motion enabled larger offset angles to be achieved. Additionally, with the rigid handle, a choice of orthogonal grasp orientation appears to provide significant

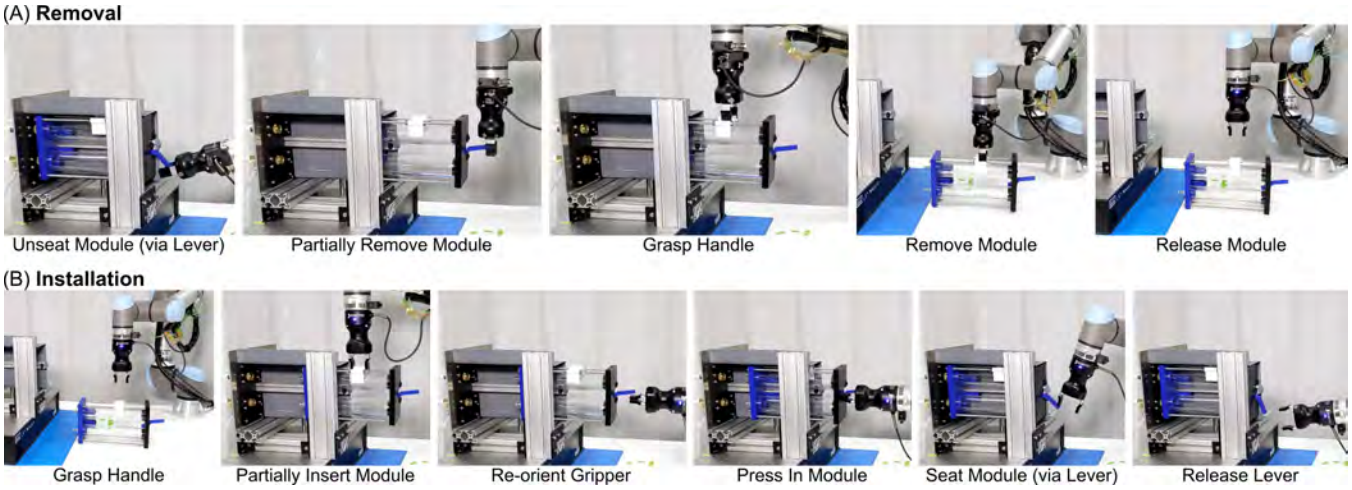

Fig. 6. Application of a “robot factors” approach to the design of an ECLSS water filter module enables a successful filter replacement task with a single 6-DOF robot arm equipped with a standard parallel jaw gripper. (A) To remove a filter, the robot utilizes the module’s lever (blue) to unseat the fluid connectors, and the handle (white) to securely grasp the module during removal. (B) To install a module, the robot utilizes the handle to grasp and insert the module, the rail system to guide the module into place while pressing it, and finally, the lever to easily seat the fluid connectors.

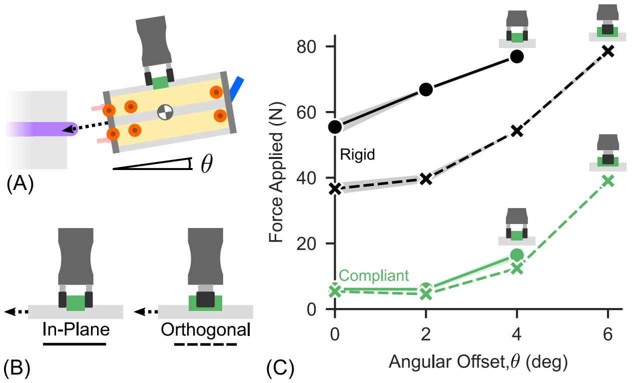

Fig. 7. The effect of angular deviation during water filter module insertion on the off-axis forces applied to the module. (A) The schematic diagram shows the module’s insertion into the chassis at an angular offset, θ. (B) The module’s handle (green) was grasped in two orientations: “in-plane” and “orthogonal” to the plane of motion. In addition, both a rigid and compliant handle were tested. (C) The resulting magnitude of force applied to the module is shown for $n = 5$ trials at each condition. The force is significantly higher when using a rigid handle vs. a compliant handle, and the rigid handle shows a large sensitivity to grasp orientation. Additionally, for both handles, grasps oriented in the plane of motion failed at angles larger than 4° due to force limits in the arm (>150 N).

effective compliance (as the handle can pivot in the robot’s grip), resulting in lower forces. With the compliant handle, however, the choice of grasp orientation does not appear to significantly affect the applied force on the module. Overall, these results demonstrate that incorporating compliance into interfaces, as well as careful consideration of grasp details for robots, can drastically improve the success of manipulation during insertion tasks.

V. DISCUSSION

The demonstrations presented suggest that the robot factors approach was successful in (1) reducing required dexterity such that module replacement tasks can be completed with a single arm and parallel-jaw gripper, (2) reducing the precision required for completing a task, and (3) lowering the forces required to complete a task. These results show how slightly increasing the complexity of a manipulated item can permit reliable autonomous operations, where much greater advances in robot sophistication would be required in order to have the same effect.

The robot factors approach involves modifying the designs of manipulated objects to avoid steps that can generally be expected to present difficulties for common robot configurations and gripper styles. Table I lists those steps of each case study which are expected to be difficult or impossible for many common robots.

Observations from the case studies lead to design principles characteristic of the robot factors approach, which could be applied to building materials, tools, or other items that are to be manipulated by robots. Principles to consider when designing such items include:

- Use simple mechanisms that consolidate compound motions.
- Constrain motion to a single axis using channels or tracks and V-wheels.
- Avoid the need for multiple arms by supporting the mass of mating parts, thereby enabling re-grasping.
- Grasp the item near its center of mass. Consider adding handles if needed.
- Introduce compliance at the interface of the gripper and the item to accommodate pose errors.
- Consider gripper orientation relative to the direction of motion.

Common to both the power module and the filter module case studies was the consolidation of degrees of free motion needed to complete the task. For the power module, the consolidation of motions afforded by the gear system allowed for multiple motions to be replaced by the pivoting of a single lever. For the filter module, the need to attach/detach hose connectors as an independent step is avoided due to

TABLE I

DESIGNING MODULAR INTERFACES WITH ROBOT FACTORS IN MIND SIMPLIFIES PREVIOUSLY-CHALLENGING TASKS

Task	**Complications**	**Solution**
Power Module		
Unlock wedgelocks	Gap between wedgelock and module is too small to be accessed by conventional grippers. Wedgelock handle must be held horizontal while removing module.	Replace with single lever
Open ejector handles	Requires bi-manual operation. Requires forces that exceed robot's limits.	
Close ejector handles	Requires bi-manual operation. Requires forces that exceed robot's limits.	
Lock wedgelocks	Wedgelock handle must be held horizontal while inserting module.	
Filter Module		
Disconnect hoses	Simultaneously retract collar (requires in-hand manipulation) and pull on hose.	Replace with push/pull connectors
Loosen captive fasteners	Locate captive fasteners and orient a wrench accordingly. Verify when fasteners are disengaged.	No fasteners, lock against rail instead
Tighten captive fasteners	Module must be precisely aligned in order for captive fasteners to engage.	No fasteners, lock against rail instead
Connect hoses	Align each hose with appropriate connector.	Replace with push/pull connectors

the kinematic coupling of the connectors with the backplane receiving the axial force given by the locking lever. Also, in both case studies the lever was used to provide mechanical advantage, thereby reducing the peak force the robot needs to exert in order to remove and replace the modules.

While module replacement could be achieved using a rigid coupling between the gripper and the filter module, we found that adding compliance between the two resulted in more reliable placement of the module, while also reducing the force required to insert the module. While humans constantly adapt to make up for relatively imprecise control of our arms, robots typically execute much more precise motion. Adding passive compliance into the gripper or object, together with mechanical features to ensure alignment as two components are mated, allows the pose uncertainty typical for mobile robots to be accommodated while still resulting in higher reliability and lower required forces.

Other factors that are generally recognized best practices were also incorporated, and can be considered as principles for robot factors:

- Use levers and gear ratios to reduce the peak force required.
- Use fillets and chamfers on corners and edges to enforce alignment and reduce collisions.
- Avoid workspace boundaries and joint limits, where accuracy and power efficiency are reduced.

Certain requirements that did not arise in the scope of the presented case studies may still be useful to consider in future scenarios. For instance, both of the example modular systems involve a step of opening and closing the cabinet door in which the respective chassis are located. Such enclosures could also be improved by considering robot factors. For instance, captive fasteners securing the cabinets shut could be replaced by toggle clamps.

A related approach frequently used, particularly for tasks that may require more elaborate perception and planning, is for physical objects to facilitate their own localization, using visually distinct identifiers (e.g., AprilTags, QR codes, or bright colors), magnets and Hall sensors, RFID tags, etc. In other applications, it may be beneficial to outfit the manipulated item with instrumentation that allows it to provide state feedback (e.g., indicating whether it has been successfully seated in its chassis, such as is described in Sec. III). Such interventions may be particularly useful for tasks where it is difficult for a robot to externally verify task execution (such as when key visual features are occluded).

The most immediate opportunities and benefits for applying a robot factors approach may be in space applications, where there is a pressing need for autonomy as well as much freedom to redesign hardware from fundamentals, as in the two case studies in this work. For both case studies, the modifications resulted in a modest increase of the mass of the module, which would correspond to an increase in launch costs. Design for the space context should seek to minimize the amount of added mass. Analyses can be performed of the tradeoffs in added mass vs. the added value of autonomous operation. Beyond space applications, the two case studies point to broader classes of terrestrial applications where robot factors could enable autonomous operation on an accelerated time scale. For example, other modular electronic systems such as PCB card racks could be modified with a robot factors approach. These systems use the same connectors and wedge locks as the AMPS modules; as discussed above, these systems require considerable dexterity and force to operate, which may be well beyond the capabilities of readily-available mobile robots.

While the explicit objective of the robot factors approach is to expand the pool of users of a given artifact to include robots, the approach can provide benefits to human users as well. In both presented case studies, the original designs required bi-manual operation, coordinated manipulation of multiple elements, and use of threaded fasteners. The modified designs, by contrast, require only one hand to operate, less dexterity, and less peak force to be exerted. As a result, they could be operated by a larger pool of human users as well, e.g., including amputees and people with limited dexterity, or under limiting conditions such as while wearing thick gloves; and unimpaired users could operate the interfaces more quickly and easily than with the original designs.

VI. CONCLUSIONS

The robot factors approach provides means by which manipulation tasks that are not currently possible with common manipulators could be made possible, on a shorter time scale than an approach based on advancing robot capabilities closer to human levels. This approach demonstrates that by making hardware slightly more sophisticated, one might reduce or eliminate the need for highly sophisticated robots. In this work, we demonstrated that several simple hardware design changes can result in devices that can be manipulated easily by a single, standard robotic arm, rather than requiring dexterous bi-manual manipulation. We also show that mechanical compliance at the interface of grippers and objects can dramatically decrease the effects of pose uncertainties and (potentially damaging) forces applied to the hardware. Finally, we consolidate the lessons of the case studies into a set of design strategies that represent a robot factors approach to hardware design.

Everyday tools, interfaces and devices have evolved over the ages to facilitate human manipulation. Getting robots to perform human tasks has proven exceedingly difficult. An alternative is presented with the robot factors approach, suggesting that redesigning devices expressly for robot manipulation might be a more expedient route to the autonomous execution of previously-impossible tasks.

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