Automated Reconfiguration of Modular Robots Using Robot Manipulators

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***Abstract*—Self-reconfigurability in modular robots is a challenging task that usually requires complex module designs and algorithms. To make the reconfigurability easier, unpowered permanent magnet-based modules can be reconfigured by an external robotic manipulator. These modules are, thereby, not dependent on each separate module's inclusion of batteries and control circuitry since they can be reconfigured in their unpowered state, and the reconfiguration movements are not restricted to the kinematic chain of the modular robot. In this paper, we discuss how we can utilize an active or passive gripper to assemble and disassemble modular robots. We furthermore demonstrate that the use of fiducial markers allows the robot arm to accurately pick and place the modules to reconfigure the morphologies. The utilization of robotic arms and a visual feedback system allows us to quickly create robot morphologies from modules, which can be evaluated in the real world and then reshaped using the same components. This technique is especially valuable to enable the rapid generation and evaluation of robot morphologies in the real world that would traditionally need to be reconstructed or reassembled with complex modules or complex attachment mechanisms.**

I. Introduction

Modular robots are able to change its morphology through reconfiguring its modules to adapt to a variety of tasks. They have two main advantages over traditional robots: (1) the robot morphology is reconfigurable, and (2) this reconfigurability allows them to perform tasks that are unknown a priori [1]. While manual assembly and disassembly has been used extensively to reconfigure the modules [2], [3], it usually requires an operator, which reduces the autonomy of these robots. The usual solution is to use self-reconfigurable modular robots that enable modules to automatically, and autonomously, disconnect from the main robot and reconnect elsewhere [1], [4], [5]. Self-reconfigurable robots are thus versatile considering their ability to change their body plan autonomously. However, the robustness of self-reconfiguration is still an issue [1] and modular robots have only been investigated in mock-up experiments in laboratory conditions, as discussed in [6] and [7] for tasks like space exploration.

The limited number of practical applications is due to several drawbacks of existing self-reconfigurable modular systems. These drawbacks include weak connection mechanisms, heavy modules, and complex reconfiguration algorithms. The weak connection mechanism and weight can be in part attributed to the active connection mechanisms. Reconfiguration of a self-reconfigurable robot requires movements of individual modules that are difficult to generate due to the limited kinematic chain of the modular robot. Some configurations are even not possible without separating modules from the robot. Therefore, in the conventional approach, modules need to have a locomotion mechanism to reconfigure to those specific configurations.

In addition, sensors are usually needed to provide a closed-loop feedback for reconfiguration [8]. This is especially complex in chain modular robots, where a solution has to be checked to see whether the formed chains are feasible [9][10]. The complexity of the algorithms required to reconfigure the modules is further increased when a composition of heterogeneous modules is used.

While self-reconfiguring modular robots enable self-adapting robot morphologies [11], [12], their range of applications is still limited. We address the reconfiguration process through utilizing a dedicated robot arm responsible for the automated assembly and disassembly of the robotic modules. A limitation of a stationary external device for reconfiguration is that the process is only possible if all the modules are near the manipulator's workspace. Apart from this limitation, through externalizing the reconfiguration mechanism, the design of the modules can be kept simple and light-weight as active connection faces are not required. This reduces the complexity of the reconfiguration algorithm since a global tracking system can keep track of the modules' location and reconfiguration is reduced to moving modules around with the manipulator.

Similar to the automated reconfiguration of modular robots using robot manipulators is the automated assembly of parts in manufacturing [13] [14]. Different manufacturing techniques have been developed, usually employing jigs and fixtures to align one part while the other part is held by a manipulator. Pick and place tasks often involve the use of a visual positioning system to allow a manipulator to handle electronic components and place them in a printed circuit board [15]. Although this work can be viewed as a pick and place problem, we argue that the scope of the addressed task is more difficult due to the lack of fixtures. In addition, the system is not only required to pick and place the modules, but also requires a means to separate them after a configuration has been evaluated.

External reconfiguration devices have also been used in modular structures to build or change their shape. These devices include manipulators [16], mobile robots [17] or drones [18]. For reconfiguring modular structures, Saldana et al. have designed decentralized algorithms for assembling different kinds of structures from mobile modular robots [19]. Furthermore, Brodbeck et al. [20] described robots composed of two different types of modules (passive and active) that are joined by an industrial manipulator with hot glue adhesives. This system can automatically test robot morphologies and controllers in an arena but it cannot disassemble the modules after a test.

Our approach comprises two main advantages over this approach: using magnets to connect the modules is faster compared to using hot glue adhesives, and, more importantly, our system is able to automatically disassemble the modules. For this reason, we investigate the mechanisms and physics involved in the attachment and detachment phases of the process, including the type of gripper and the forces affecting the magnetic connectors of the modules when approaching one another

Section II presents two alternatives for the robot arm reconfiguration process and a brief description of the EMERGE platform. A theoretical magnetic force analysis of the module connectors is presented in section III. Section IV describes tests performed with the two alternatives and their results. Finally, we discuss how the two approaches can result in a useful implementation of reconfigurability in modular robots.

II. Methodology

Our methodology comprises two main elements: a chain modular robot without self-reconfiguration capabilities and two different robotic arms that reconfigure the modules. Both robot arm approaches use a gripper which defines their interaction with the module and the way in which modules are attached or detached from a given morphology. All the components are described in the following subsections.

A. EMERGE Modular Robot

The EMERGE modular robot[1] is a platform designed to be easy to build, which enables us to assemble morphologies quickly [21]. Each module resembles a small cubewith a central hinge, which is comprised of a central servo motor with a pair of brackets screwed to the motor axle and to the bottom of the servo motor. Attached to the brackets are faces that contain printed circuit boards (PCBs), which route communication and power inside the module. 3D-printed mating magnetic connector faces, with the male connector having protrusions that match holes in the female, maintain mechanical and electrical connections between any two modules (Figure 1).

[1]The design is open source and is available at https://sites.google.com/view/emergemodular/

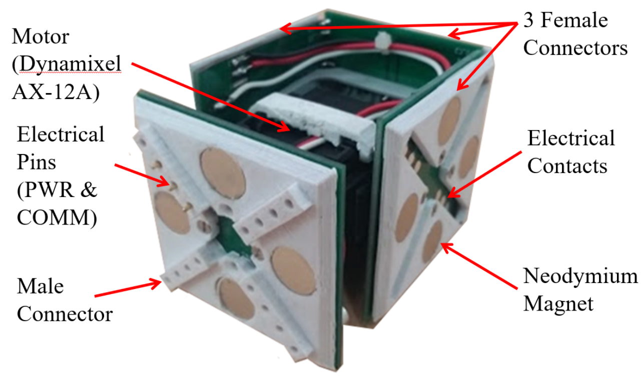


Fig. 1: The Emerge robotic module.

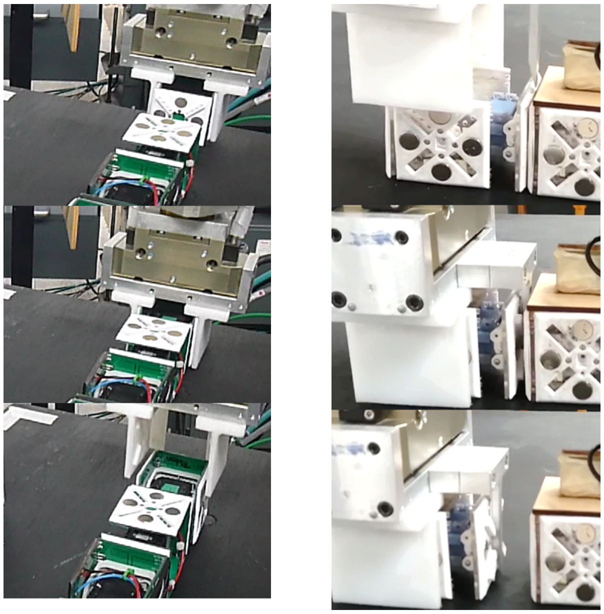
B. Active gripper approach

The first alternative for the automatic reconfiguration problem uses a gripper with active parts attached to a Yaskawa MH6 Motoman robot manipulator (Figure 2). The gripper uses two moving fingers that close around and hold one EMERGE module (Figure 2a). A secured module can then be positioned and oriented in order for it to be connected to another module. To disconnect modules, a knife part (5mm thick) was introduced between connectors to separate them, after that the free module was held by the active fingers and put in a place where it could not connect anymore to the morphology (Figure 2b).

Unfortunately, the application programming interface (API) of the robot was not available at the time of implementing this work; therefore, we could not use a visual feedback system to track the positions of the modules. Instead, we used the teach pendant to record the movements of the robot and place the modules where we want them to be picked up. The procedure is: (1) position the gripper above a module ensuring the alignment of the active fingers with the module's shape, (2) move the gripper down until the module is covered, (3) close the active fingers around the module, (4) lift the module up to a safe distance above the floor, (5) move the end effector to the side of another module, (6) move the end effector down, (7) move the end effector toward the other module's attaching face, and (8) release the module by opening the active fingers. Similarly, to detach a module from a 2D morphology: (1) move the gripper above the desired module, (2) align the knife with the module's connection with the other modules, (3) move the gripper down to make the knife separate the connection, (4) close the fingers around the module and (5) move the module away from the other module.

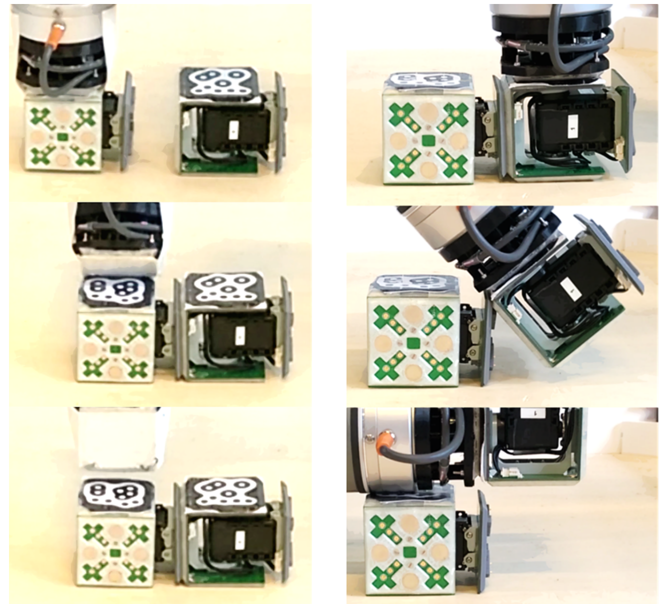
C. Passive magnetic gripper approach

The second approach uses a magnetic gripper attached to a Universal Robotics UR5 robot manipulator. The gripper utilizes permanent magnets and therefore the detachment of the modules is solely based on the movement of the robot's end effector (Figure 3). Assembling a module to a robot morphology is done by attaching one face of the module



(a) (b)

Fig. 2: Attachment and detachment mechanisms using an active gripper approach. The gripper uses two moving fingers to close around and hold one module and a knife to separate two connectors. (a) depicts the attachment of module to a morphology. (b) shows how a module is detached from another by using the knife to separate the connectors.



(a) (b)

Fig. 3: Assembling and detachment approach of the modules using the passive gripper. (a) depicts the attachment of a module to another and the subsequent release of the module. (b) shows the process of detaching a module from another module.

to the magnetic passive gripper (Figure 3a). However, since the gripper doesn't have moving parts, to detach the gripper from the module the end effector must describe an arc move with center on one of the connector edges in a direction perpendicular to the male connector protrusions. A similar movement is performed when detaching a module from a robot morphology (Figure 3b), the main difference with the assembly movement is the direction of the movement.

For the passive gripper approach, a visual positioning system was available (Figure 3). This system works by placing fiducial markers on one face of each module and using a web-camera placed above the arena to track their positions and orientations on the ground. An affine transform is used to translate the pixel coordinates of the positions in the reference system of the robot. In order to automatically create this transform, four fixed markers with known positions in the reference system of the robot are placed at the corners of the arena. Movements of the robot manipulator can then be programmatically generated based on the current positions of the modules and their target positions in the configuration[22].

The basic steps are: (1) move end effector above the marker, (2) align end effector with the marker, (3) move the end effector down until 30N are applied (this avoids jamming and ensures that the module is well connected to the gripper), (4) lift the module up to a safe distance above the floor, (5) move the end effector to the side of the module to be attached, (6) move the end effector down, (7) move the end effector towards the other module's attaching face, and (8) based on the position of the arm, perform the movements to release the module which is attached to the gripper.

D. *Limitations of the current methodology*

In both approaches, only 2D modular robot morphologies are considered. This is because there is no disconnection mechanism embedded in the connectors of the modules. Therefore, we need to compress the modules against the floor to be able to hold the module in place. However, even with this restriction a great variety of morphologies are still possible.

A disadvantage of using the visual positioning system is that modules have to be oriented with their fiducial markers facing the camera. So the system is not able to work with modules in different orientations to the ground plane since the markers can only currently be placed on the robot faces. Furthermore, the markers are glued to one of the female faces of the module, which reduces the versatility of the system. We are working towards a design of the modules that integrates markers in all sides. In addition, we are also working on a system that can extract the position and orientation of the markers independently of their place in the module.

III. Magnetic connector force analysis

To study the behavior of the EMERGE module's magnetic connector in regard to the automatic assembly and disassembly with the active and passive approaches, we modeled the forces between magnets by using a dipole field model [23]. In this

TABLE I: Magnet properties

Quantity	Value	Units
D	12.7	mm
t	3.175	mm
Br	1.32	Tesla
cf	1/10.618	-
μ_0	$4\pi \times 10^{-7}$	N/A^2

model, each magnet is represented by a moment $\vec{m}$ (a vector in 3d space) that can be approximated by Equation 1.

$$\vec{m} = \frac{V \cdot Br}{\mu_0} cf \hat{u} \tag{1}$$

V is the volume of the magnet calculated as a cylinder with diameter D and thickness t, Br is the residual induction of the magnet, μ_0 is the vacuum permeability, and $\hat{u}$ is the unit vector. The magnet properties used in this work can be seen in Table I. A correction factor cf is introduced to adjust the model due to non modeled phenomena. The field generated by a moment $\vec{m}$ can be calculated as:

$$\vec{B} = \frac{\mu_0}{4\pi} \frac{(3\vec{m} \cdot \vec{r})\vec{r}}{\|\vec{r}\|^5} - \frac{\vec{m}}{\|\vec{r}\|^3} \tag{2}$$

where $\vec{r}$ is a vector going from the magnet's position to the point of interest. The field generated by multiple magnets is calculated independently and then summed at the point of interest. To calculate the force that a magnet $\vec{m}_0$ exerts on another magnet $\vec{m}_1$ first the field generated by $\vec{m}_0$ ($\vec{B}_0$) is calculated in the position of $\vec{m}_1$.The force $\vec{F}$ is then:

$$\vec{F} = \nabla(\vec{m}_1 \cdot \vec{B}_0) \tag{3}$$

To find the force that one EMERGE connector exerts on another, we place one connector at the origin of a Cartesian coordinate space facing in the positive X direction (Figure 4). Another connector is then placed at the positions and orientations of interest and the force exerted is calculated using the dipole field model. The simplicity of this model limits its applicability to cases where magnets are away from each other, however, it can still produce a good estimate of the forces involved. Using this setup, three cases related to the reconfiguration process are considered:

- *Force between two separating aligned connectors:* The force between two connectors aligned at the center while being separated along the x axis can be seen in Figure 5. Both connector magnets moments are placed so that they attract each other. The minimum separation distance for one module to be held by friction (F_f, wood table in contact with 3D printed ABS) was measured experimentally using the setup in Figure 5. One module was fixed and the other released from different positions with their connectors aligned. After 20 measures the minimum distance was found to be 20 mm $\pm$ 1mm. The force of the connector was also measured at specific distances to validate the model and tune the correction factor in Table I.

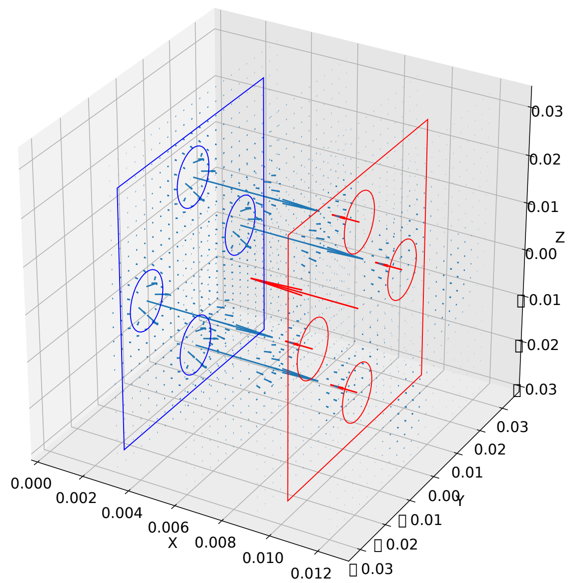


Fig. 4: Connectors magnetic model: One connector is placed at the origin of a Cartesian coordinate space facing the positive x direction (left-blue) and the field due to its magnets (blue arrows) is calculated. A second connector (right-red) is placed in front of the first one. Force at the second connector magnets is found using the dipole field model (red arrows), the arrow at the center of the second connector is the sum of all four magnet forces.

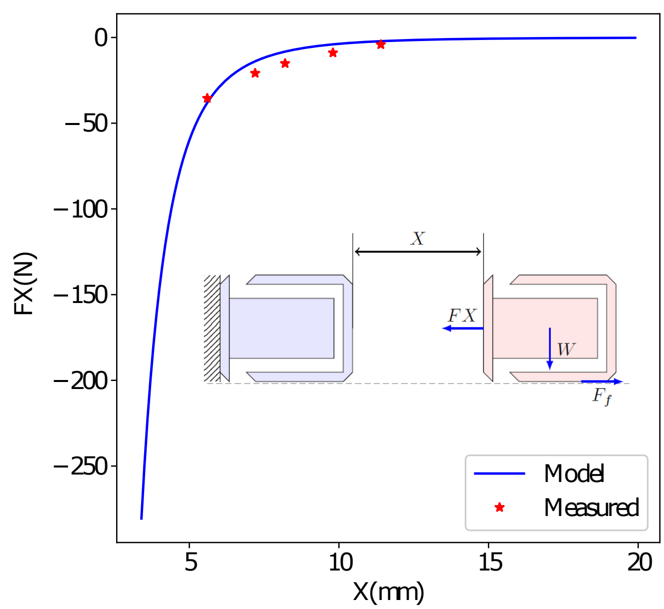


Fig. 5: Force between two connectors aligned at the center (Figure 4) when their separation distance in x is varied (inside diagram). Friction forces are denoted as F_f. Red dots show the average measured force of the real connector at distances of: 5.6, 7.2, 8.2, 9.8 and 11.4mm

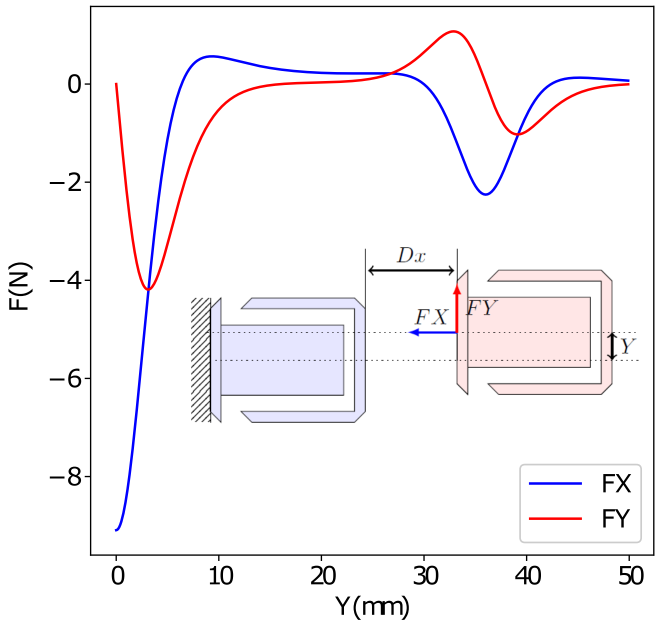


Fig. 6: Force between two connectors separated by fixed distance (Dx) of 8mm in x from each other, when y is varied (inside diagram)

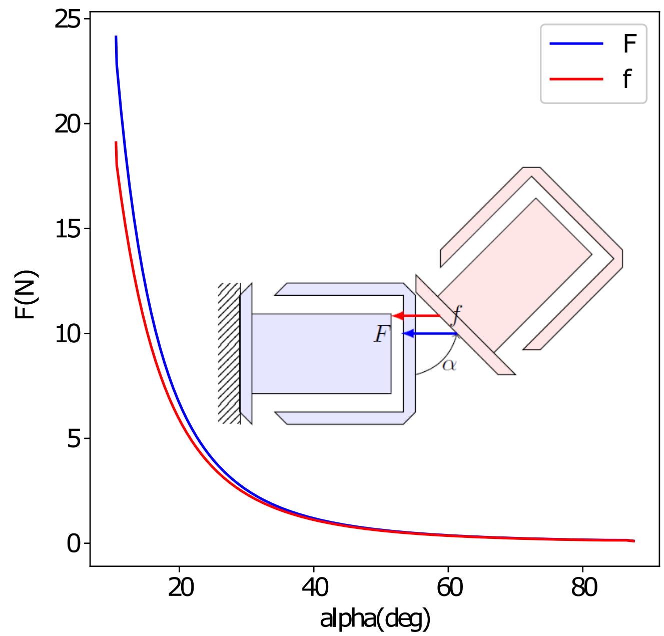


Fig. 7: Forces between two connectors being separated by the detach movement of Figure 3. The magnitude of the total force (F) on the connector is compared with the magnitude of the force on the magnet closer to the center of the movement (f).

- *Forces between misaligned connectors:* The force between two misaligned connectors can be found by initially placing the second connector at a fixed distance from the origin one in X and varying the distance in Y (Z remains fixed at 0). The force sampled as Y is varied can be seen in Figure 6. The resulting FY force helps correct small misalignments in the assembly process, but can provoke the same misalignments in the disassembly process.
- *Forces between connectors separating at an angle:* The forces between two connectors being separated by the detach movement of Figure 3 can be seen in Figure 7. Figure 7 shows that the force on the magnet closer to the center of the movement decreases slightly slower than the overall force on the connector. This magnetic force prevents the connectors from separating, which is solved by continuing the movement until the two connectors are perpendicular to each other (Figure 3b).

IV. Automatic Assembly

The active and passive gripper approaches were evaluated differently, which will be discussed next.

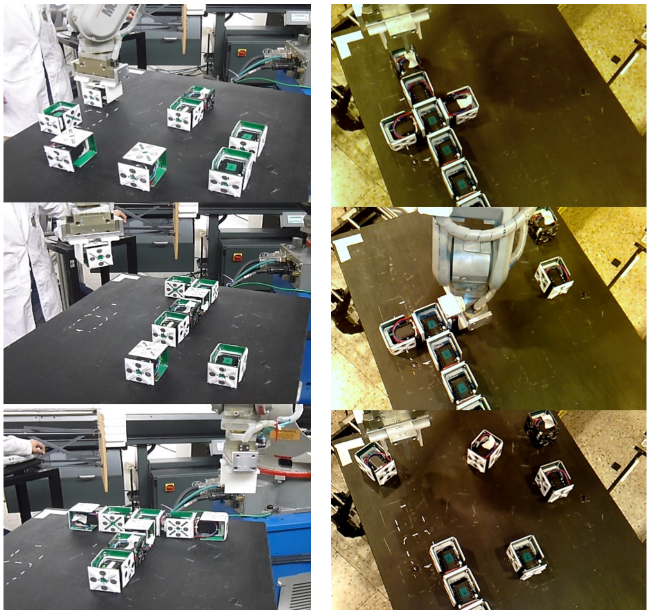
A. Active Gripper

Using the attachment and detachment movements described in Figure 2, two tests were performed using the active gripper approach.

In the repeatability test, two planar robot configurations with 8 modules each were repeatedly assembled and disassembled (10 times) to check for any kind of problem that could arise in the process. Figure 8 shows the assembly and disassembly process carried out with the two configurations. For the assembly process, the knife is detached from the gripper. As the system lacks a visual positioning system, individual modules are placed in predetermined positions on the table, then the robot arm travels to each module, secures it with the gripper, and moves it to its destination.

The experiments determined that misalignments are less likely to affect the assembly process due to the connector's self centering forces, analyzed in section III, and also because modules are separated enough for the manipulator to correctly align one connector face to the other. As a consequence, all 10 trials were successful. During the disassembly process, movements of the whole structure due to a module being separated were greater than expected, thus the structure's position had to be manually corrected. This problem increases as fewer modules remain in the structure, that is, friction forces are not enough to oppose the magnetic connector forces and modules can be moved further distances (section III and accompanying video [24]), this problem shows that a positioning system is necessary for the automatic reconfiguration to work properly.

The force that the knife needs to apply in the downward direction (G in Figure 9) to separate one module from a robot morphology is measured using the robot's equipped sensors. For this purpose, the torques in each of the robot's motors are registered as the knife's tip moves down. The force is then calculated based on the total torque and the position of the knife relative to the robot arm. We performed 10 measurements



(a) (b)

Fig. 8: Assembly and disassembly process carried out in the repeatability test with the active gripper. (a) shows three frames of an assembly process with an 8 module configuration. (b) shows three frames of a disassembly process with another 8 module configuration.

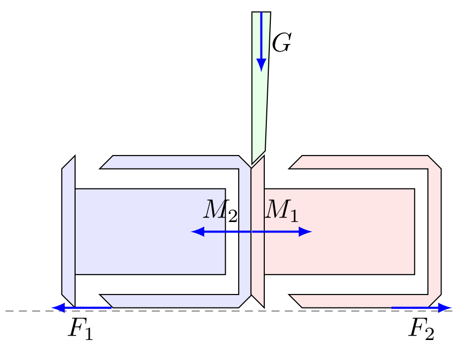


Fig. 9: Force (G) used by the active gripper's knife when separating a module from a planar robot morphology. F_1 represents the friction force of the rest of the modules attached, F_2 is the friction force of one individual module with the ground

and the average maximum force was found to be 5.4 N $\pm$ 0.1N. This low force ensures that the disassembly process using the active gripper can be done with less powerful robot manipulators.

B. Passive Gripper

The passive gripper system was tested by assembling and disassembling a specific morphology (refer to the accompanying video [24] or figure Figure 10). Using visual feedback, the robot arm localizes the modules and attaches to them. After a module is picked up, the movements depicted in Figure 3a are used to release the module from the gripper. To disassemble a robot configuration, a movement similar to the one depicted in Figure 3b can be used.

The assembly and disassembly of this morphology was tested 10 times without problems. The disassembly was more challenging and sometimes the robot arm could not finish it correctly. The main problem that we found was that the movements the end effector should perform are sometimes near singularity points, which raise a safety stop in the robot arm. Additionally in some positions, the end effector causes the attached module to press onto the floor of the arena. This force is later detected by the robot arm, which also produces a safety stop. Both problems could be improved by modifying the software that generates the trajectories of the robot.

V. Discussion

Our approach to the automated assembly and disassembly of modular robots allows us to automatically reconfigure robotic structures by using a simple robotic module in conjunction with a manipulator. This is specially useful in chain type modular robots, where self-reconfiguration is limited due to kinematic restrictions. In addition, it is useful for rapidly prototyping and deploying robots to perform different tasks. In this platform, the morphology of the robots can be optimized, possibly with the aid of simulation environments. Although the analysis of the connector shows that it can apply a self-centering force and tests showed that this force simplifies the assembly of the structures, it also makes them more difficult to disassemble. Therefore, a positioning system, i.e. visual feedback, is necessary for the robot manipulator to keep track of modules that move due to disassembling forces. This positioning system is important for an eventual implementation of automated evolution of morphologies since the robotic manipulator needs to be able to reconfigure a robot after it has been active in its environment. We proposeto merge the two gripper approaches, using the positioning system, in one robot manipulator in future implementations of the system.

Some challenges remain to be addressed in order to improve the system to a state where continuous experiments can be done with reconfiguring robot morphologies. As stated in subsection II-D, visual fiducial markers can only be currently attached to the modules at specific parts. They also obstruct the correct functionality of the connectors they are attached to. Thus, a redesigned fiducial marker or another way of recognizing the robot modules should be used. Another limitation of the current setup is that the robot is unable to be controlled and acquire power without the help of an operator attaching a control cable to one of the modules.

To have a fully automatic process, a base module that couples to a docking station can be implemented. The base module/docking station assembly can then be used as the initial point from which robot morphologies are assembled. Battery modules with wireless capabilities can also be added to the system for when the assembled robot must move away from the docking station. Only planar configurations (one layer of modules) were considered in this work, and 3D

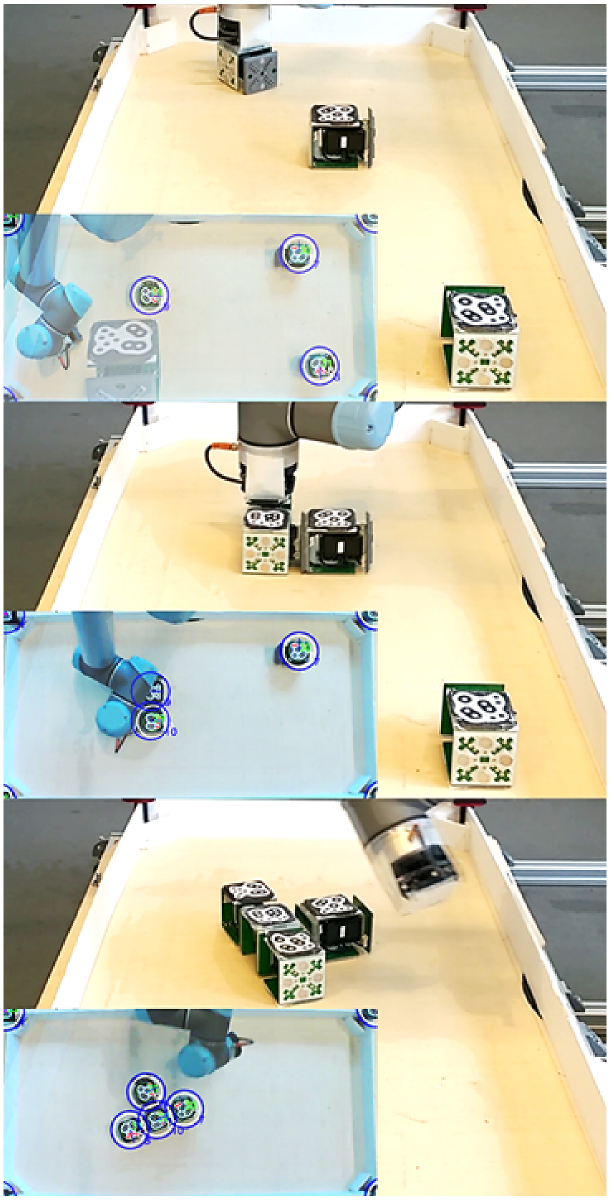


Fig. 10: Three frames taken from the assembly process carried out with the passive gripper approach. Bottom left depicts the visual feedback system with circles representing the positions of the fiducial markers.

configurations still present a challenge as they would require more complex reconfiguration movements and adjustments to the visual tracking system.

Automatic reconfiguration can be specially beneficial in fields that optimize the morphology and control of robots [25]. It can be specifically well suited for evolutionary robotics experiments that are usually time consuming due to the number of morphologies that need to be tested. Although some approaches already show promising results by implementing evolved robots in simulation environments and afterwards transferring them to the real world [3], [26], they are still time consuming considering that all parts have to be glued or screwed together. This is also addressed in [20] by using an evolutionary algorithm to generate the robot morphologies, however, our approach allows for different robot morphologies to be more quickly tested in a real environment and can therefore be suitable for online-evolution [27] as well as for a combined approach of using simulation to optimize the robots and then transferring the best performing ones to the real world. This can, furthermore, give insights in reality gap related issues making the automated creation of robots more feasible.

VI. Conclusion

We have shown that it is possible to automatically assemble and disassemble modular robots using a robot manipulator as an alternative to self-reconfigurable robots and manual reconfiguration systems. The benefit of this platform is its potential use in the automated alteration of robot morphologies that would otherwise require laborious hours for a human operator. This automatic reconfigurability enables the fast prototyping of different robotic morphologies and control systems, which gives us insights in how to construct an efficient robotic end-product for a given task. Although some challenges need to be addressed in order to have a fully automatic system, the basic functionality of the automatic assembly/disassembly process has been demonstrated using an active and a passive gripper approaches. Experiments indicated that the self-alignment force of the connectors aids in the assembly process of the modular robot but displaces the modular robot while disconnecting a module. Therefore, a visual feedback system, or another positioning system, benefits the reconfiguration procedures of the system. We expect that the presented platform would greatly benefit from the addition of a base module/ docking station to remove cable requirements and increase the platform's autonomy. These additions would make the platform presented well suited for automatically optimizing the morphology and control of the modular robots, through using evolutionary algorithms for example.

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