Towards a modular robotic platform for construction and manufacturing

Jose-Alfredo Leal-Naranjo, Sebastiano Fichera, Paolo Paoletti

***Abstract*—Modular robotics is a promising approach to tackle modern societal challenges spanning from search and rescue missions, to smart manufacturing and construction, immersive visualisation etc. However, open mechatronic and control challenges still hinders this technology from achieving its full potential. A modular robotic system capable of reconfiguring itself in a 3D is proposed in this work. Such a system is intended to set the basis for a new methodology for manufacturing smart products and structures that can dynamically respond to external stimuli and user's commands. Each robot is a 100 mm cube able to perform 3D reconfiguration using three actuators only. A detailed description of the mechanical and electronic systems is discussed, along the communication strategy needed to exchange information between modules. Multimaterial 3D printing is extensively used to reduce the number of required parts. Three modules were built to show the feasibility of the proposed design, and a set of experiments were performed to demonstrate the reconfiguration capability of the system.**

***Index Terms*—Self-reconfiguring, modular robots, autonomous systems, programmable matter.**

I. INTRODUCTION

Nowadays, most of the manufacturing processes make products that, once finished, preserve their shape and physical properties with minimal changes during their life cycle. Furthermore, once a product is not needed anymore, it either becomes waste or needs to undergo recycling processes which may be time and energy consuming. Modular robotics [1] and programmable matter [**?**] are promising approaches to overcome the limitations of current manufacturing techniques. Within these frameworks, objects, structures and products are composed by (potentially a very large number of) individual robotic units, coordinating and self-assembling to form the desired shape.

In this work, we propose a design for modular self-reconfigurable robots (MSR) to create smart dynamic products. Such products will be able to change their shape in response to external stimuli, making them dynamically adaptable to different uses and environments, something that is not achievable with current approaches. This will be achieved by designing smart programmable units, that can dynamically reconfigure in 3D to form complex structures, sense the environment and respond accordingly, all based on distributed coordination algorithms. The use of MSR would also allow energy- and material-efficient repair of end-products by simply changing the faulty modules. In addition, the recycling process would become trivial: the robots composing a no longer desired product will readily be reconfigured for creating new products.

Modular self-reconfigurable robot systems consist of several repeated modules that can rearrange themselves in different configurations [2]. These systems can be classified into different categories according to their reconfiguration capabilities. The *lattice* architecture allows the units to be arranged and connected in a regular pattern. The *chain* or *tree* architecture consists in units connected in a chain topology. System with *hybrid* architecture possess features of the lattice and the chain systems [3]. *Mobile* architectures have modules that use the environment to manoeuvre around and are able to form chains or lattices [4]. Most recently, *truss* structured systems have been proposed to form structures using links and joints, as well as the *free-form* architectures where the system forms random structures in 2D [5].

In recent years, many self-reconfigurable robotic systems have been proposed showing different types of actuation and attachment mechanisms [6], [7], with most of them being able to perform basic 2D reconfiguration tasks only. One of the most capable systems is the *3D M-block* proposed in [8]. Such a system is able to perform 3D reconfiguration of 50 mm cubical modules. An inertial actuator inside the cube can be oriented in such a way that the cubes can pivot about its edges, rotating by π or $\pi/2$ radiant at each move. The modules attach to each other by means of magnets fixed in each face. On the other hand, the field of programmable matter had mostly focused on the development of algorithms for reconfiguration [3]. However, a significant exception is the *robot pebbles* platform proposed in [9] and composed of 12 mm cubical modules. The modules use electro-permanent magnets to attach to each other, and reconfiguration is limited to self-disassembly performed by detaching the unnecessary modules from the structure.

Even though MSR systems promise advantages as versatility, robustness and low cost, the models proposed in the literature have not been tested on large scale yet, and their application is still limited to research purposes only. An interesting and more mature application of MSR are the *Roombots* described in [10], which are used to create adaptive furniture. Each module consists of four interconnected hemispheres with a size of 220 mm by 110 mm by 100 mm, and weighting 4 kg. Each Roombot has three degrees of freedom (DoF) and 10 connection plates, of which only two can perform

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active latching. A similar approach, although with different geometry, has been recently proposed in [11] as well.

This work proposes a mechatronic design and physical prototype of a modular self-reconfigurable platform capable of performing 3D reconfiguration and solving some of the outstanding challenges of the platforms described above. The paper is organized as follows: Section II presents the mechatronic design of the individual modules. Section III briefly describes the electronics embedded in the modules and discusses the challenges related to the communication between modules, together with a potential architecture to solve such challenges using common protocols. The first module prototypes are presented in Section IV, together with a set of experiments demonstrating the reconfiguration capabilities. Final remarks and directions for future work are discussed in Section V.

II. MECHATRONIC DESIGN

The proposed modules are 100 mm cubes integrating all the power supply, microcontrollers, actuators and communication buses needed to self-assemble in different shapes. A CAD design of an individual module is shown in Fig. 1a, whereas Figs. 1b-1c show the basic π and $\pi/2$ movements used for reconfiguration. Considering that a large number of modules would be needed for making a product, bespoke solutions where designed to reduce as much as possible the amount of number of components and assembly steps without impairing the platform functionality. For example, the outer shell was designed so that it can be 3D printed in one go, to minimise the need for manual assembly. Similarly, another major goal was minimising the number of actuators driving reconfiguration and docking, so that assembly, wiring and control are simplified.

This section describes the main mechanical sub-systems composing each module, i.e. the mechanism used to drive the reconfiguration shown in Fig. 1b-1c and the docking system designed to lock the modules in place and provide structural stability to the assembly. The electronic system and the associated inter-module communication protocol are described in the following section.

A. *Reconfiguration system*

The reconfiguration system is the key enabling subsystem for the shape-changing capabilities of the proposed platform. Four gates were integrated in each face of the modules, connected to the centre of every edge via a pin joint. These gates can rotate up to $\pi/2$ while pushing the adjacent modules. Such action induce the rotation of the module around the edge where the active gate is located. Of course, only one gate per module is allowed to move at any given time, to avoid conflicts.

The gates are moved by a leadscrew-based main actuator located inside the robot and shown in Fig. 2. The actuator has one translational and two rotational degrees of freedom (DoF) distributed in such a way that the leadscrew can reach all the gates. The first DoF is actuated by means of a gearmotor (1^{st} actuator in Fig. 2) via a set of pulleys and cables. This rotation has a range of motion of 2π around the axis (shown with a red dotted line). The second DoF is actuated by the 2^{nd} motor shown in Fig. 2, allowing a range of motion of π around the axis (shown with a blue dotted line). Finally, the last DoF consists of a leadscrew that translates through a threaded-spur gear. The latter is actuated by means of the gearmotor indicated as 3^{rd} motor in Fig. 2.

To prevent relative motion between two modules during reconfiguration, and therefore prevent failures, a pin is integrated in each gate. Such a pin gets pushed into a socket on the corresponding gate of the other module when the leadscrew pushes from inside. A passive 3D-printed spring mechanism embedded in the gate itself makes the pin to retract when the leadscrew does not apply any force, see Fig. 3.

B. *Docking system*

A docking system is needed to provide structural integrity to the structure once formed. In the proposed platform, docking is performed by means of a set permanent magnets fixed in each face of the modules and a couple of magnets, with opposite polarity to the ones previously mentioned, mounted on a part that can rotate inside the robots, see Fig. 4. The array of magnets satisfies a $\pi/2$ symmetry. This symmetry allows connection between any face of each module to another one, overcoming the disadvantage of some designs where attachment is only possible between some specific faces. In addition to the magnets, a set of spring-loaded pins and electrical pads are located in the faces of the modules to enable communication amongst modules, as explained in the next section. This docking system is genderless, i.e. any face of a module can dock with any face of another module irrespective of their relative orientation.

During the detachment process, as the leadscrew pushes the backplate of a gate, a wedge located in the backplate induces rotation of the internal part that houses the magnets, as shown in Fig. 4b. This rotation creates a shear force between the mobile and fixed magnets of both modules. Given that the shear force required to separate magnets is lower than the normal force needed to pull them apart, this mechanism allows strong bonding when docking and easy detachment during reconfiguration, without requiring any extra actuator or consuming any electrical power.

III. ELECTRONICS AND COMMUNICATION

The mechatronic design described in the previous section has been devised to minimised the number of actuators required for reconfiguration and docking. Nevertheless, significant challenges still remain in integrating all the required electronics inside each module to: i) control the actuators, ii) allow communication between modules and iii) implement the control and coordination algorithms driving the behaviour of individual modules and of the whole structure. In this section, the solutions developed to tackle such challenges are discussed.

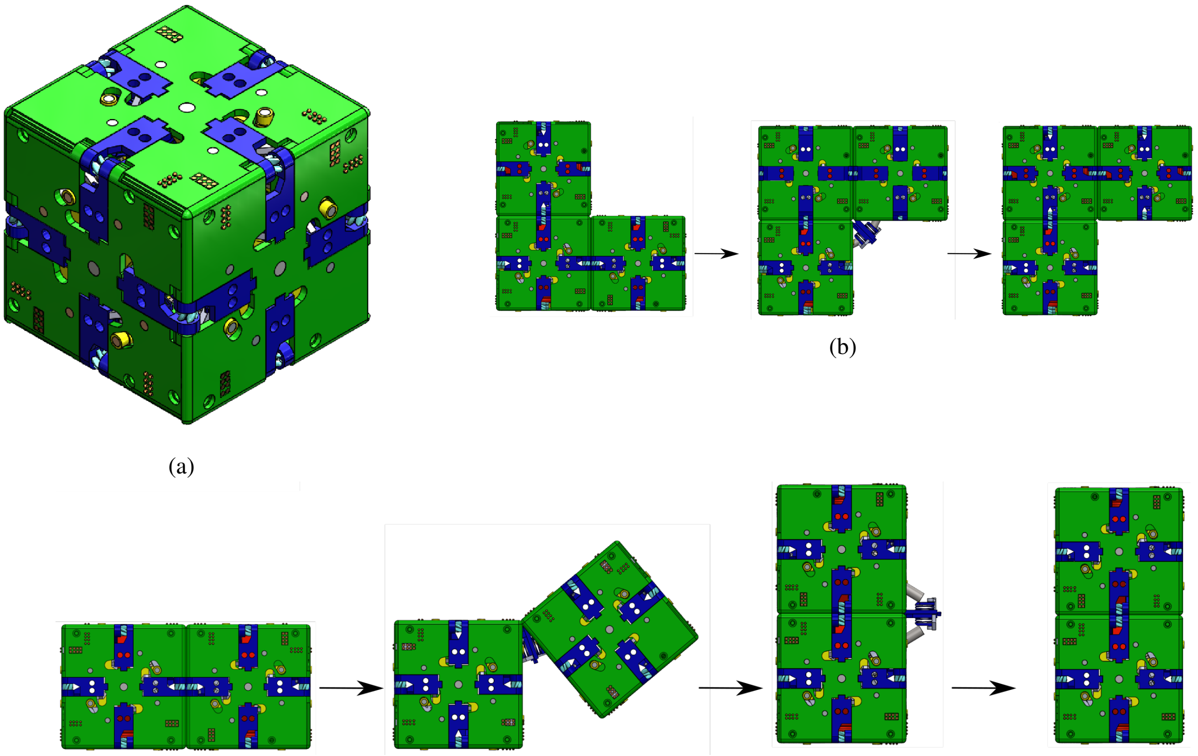


Fig. 1: Proposed platform: (a) CAD design of the a module; (b) 90°movement; (c) 180°movement.

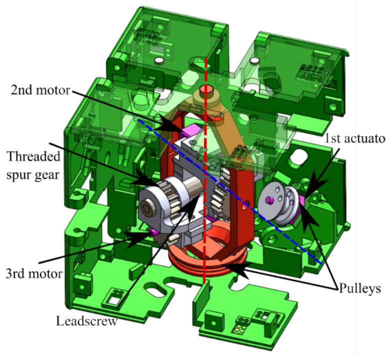


Fig. 2: Main actuators embedded in each module.

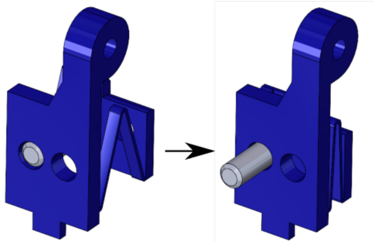


Fig. 3: Movement of the gates

A. *Electronic system*

The electronic system embedded in each module is composed of a microcontroller, three motor drivers and encoders for the motors and a communication bus to allow module-to-module communication.

The set of design requirements for the selection of the microcontroller was determined according to the following criteria:

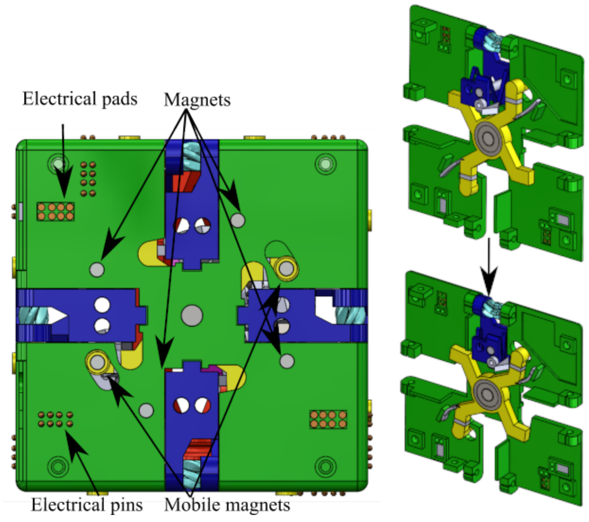
- Number of communication ports, to allow module-to-module communication.
- Number of PWM ports, to drive all the motors in the module.
- Quadrature encoder interface, to be able to measure the angular position of the motor shaft and, hence, the position of the leadscrew used for reconfiguration.
- Number of extra general purpose input/output (GPIO) pins, to allow addition of extra functionalities in the future, as the use of IMU sensors for orientation and strain gauges to measure shear forces.
- Availability of a development board, to speed up development.

Since each module can have at most six neighbours and may need to communicate with each of them during reconfiguration, the amount of communication ports should be at least one per each face of the robot. Therefore, the embedded microcontroller needs to have at least six ports. Moreover, each motor used by the modules for reconfiguration needs one independent PWM signal, therefore the required number of PWM ports is three. Furthermore, quadrature encoder interfaces are desired since they allows to easily track the relative position of the actuation motors using a dedicated peripheral to detect the signals of the encoder. Again, one encoder interface per motor is needed, therefore three interfaces in total. Considering the GPIOs for the communication, the encoder, and for driving the motors, the minimum number of GPIO pins is 57. Finally, to accelerate development, it is important to have access to a commercial development board to reduce the time of prototyping.

The STM32F767 microcontroller is capable of meeting all of these design requirements and was therefore chosen as the preferred option for the proposed modules. To interface the microcontroller with the motors, a L293D drivers composed of four half H-bridges was selected, alongside a set of limit switch sensors to detect the event of motors reaching their limit of motion.

B. Communication protocol

The modules must be able to communicate with each other to collectively complete any reconfiguration task. In the proposed platform, modules can connect and communicate to each other by means of spring-loaded pins and electrical pads located in all of their faces, as shown in Fig. 4a. The SPI communication protocol was chosen as preferred communication protocol in this work, thanks to its peer-to-peer nature that simplifies coding communication algorithms and avoid conflicts. SPI communication uses four wires: Serial Data Out (SDO), Serial Data In (SDI), clock signal (SCLK) and Chip Select (CS). In the SPI protocol, the communication is started by the controller by acting on the CS line to select a slave, and then data is sent and received in full-duplex. In its naïve form a single master would be controlling the other peripherals, but in the fully-distributed platform proposed here there is no master decided a priori.



(a) (b)

Fig. 4: Docking system: (a) Location of the fixed and movable permanent magnets; (b) Movement of the movable magnets.

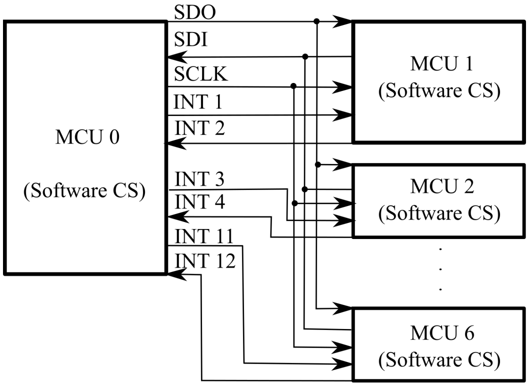


Fig. 5: Communication architecture .

To allow dynamic master selection in the set of modules, and to reduce the number of ports and physical pins needed for the communication, a different approach was adopted. The connection between the modules is illustrated in Fig. 5. During stand by, all the modules work as a SPI peripherals. For the sake of clarity and without loss of generalisation, let us then assume that MCU 0 needs to communicate with MCU 1. To achieve this, MCU 0 needs to become a SPI master first. This is achieved by setting the role of MCU 0 to master in the firmware. After that, the MCU 0 sends a pulse to MCU 1 through the GPIO labelled INT 1, thus raising an interrupt in MCU 1. The interrupt service routine will then prepare MCU 1 to exchange messages with MCU 0. After the communication is completed, the MCU 0 becomes again a SPI slave and another module can become a master when required.

Besides working as a connection for the communication, the electrical pins of the modules have other important functions as well. Two of the pins are used to transmit power across modules. The remaining pins are used to measure the relative orientation of neighbouring modules. This is achieved by placing the pads and coding their connection, so that for any relative orientation a specific connection between the pin and the corresponding pad. If the signal of two pins of each set of spring loaded pins are recorded, and in one pad two pins are set to 0,1 digital values, and 1,0 on the other pad, then for each possible relative orientation the measured signals will be [0001], [0010], [0100] and [1000]. Such information on the relative orientation is then used by the modules to decide which gate should move to achieve a desired configuration.

IV. EXPERIMENTS AND RESULTS

A set of prototypes of the proposed platform were manufactured and assembled for testing the reconfiguration capability, see Fig. 6a. Most of the parts were built using PLA material in a multimaterial fused deposition modeling 3D printer (Ultimaker S5). The frame of the robots was

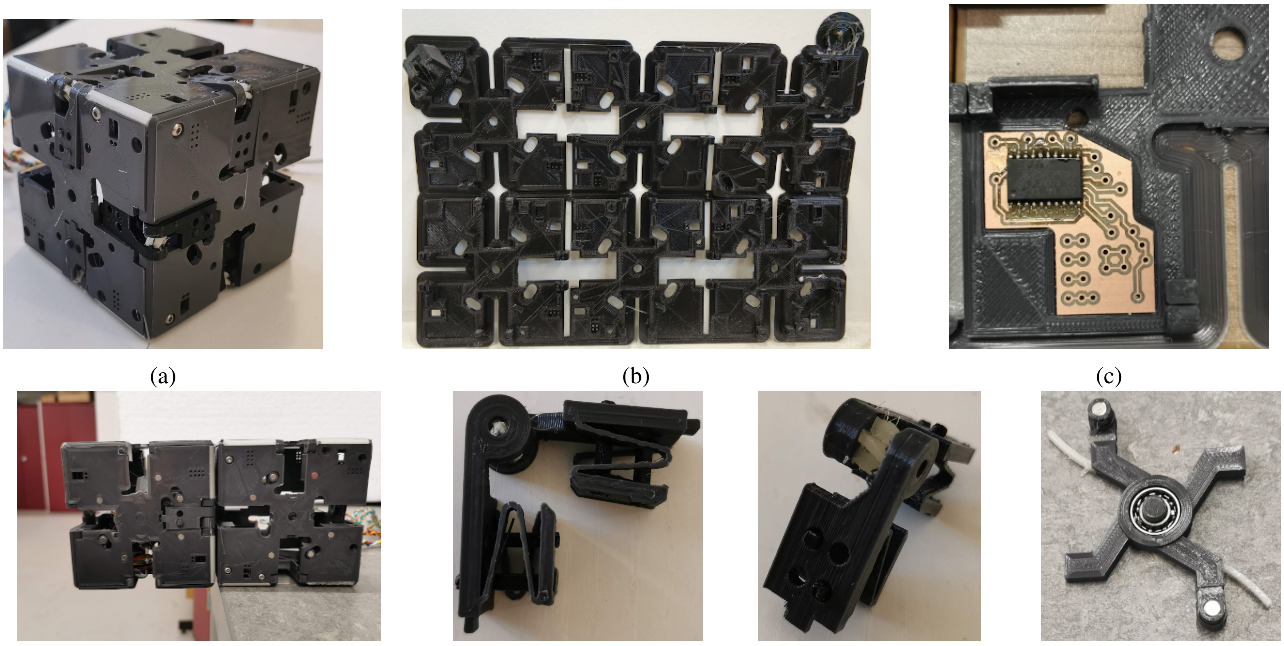

(a) (b) (c) (d) (e) (f) (g)

Fig. 6: Prototype of the proposed module:(a) Frame assembled; (b) Faces of the module printed in one batch; (c) PCB for the motor driver; (d) One module supporting the weight of another one; (e) 3D printed gate showing the springs; (f) Gate showing the compliant joint; (g) Base of the mobile magnets with springs and compliant joints.

divided in two parts, each of them having 3 faces of the cube joined by compliant TPU joints, see Fig. 6b. Thanks to such compliant joints assembly of internal components can be performed on a flat shell, before folding it into the final cubical shape. In the interior of some faces, a pocket was designed to house parts of the electronic system, see Fig. 6c. The magnets are strong enough for one module to withstand the weight of another one in a horizontal chain, see Fig. 6d.

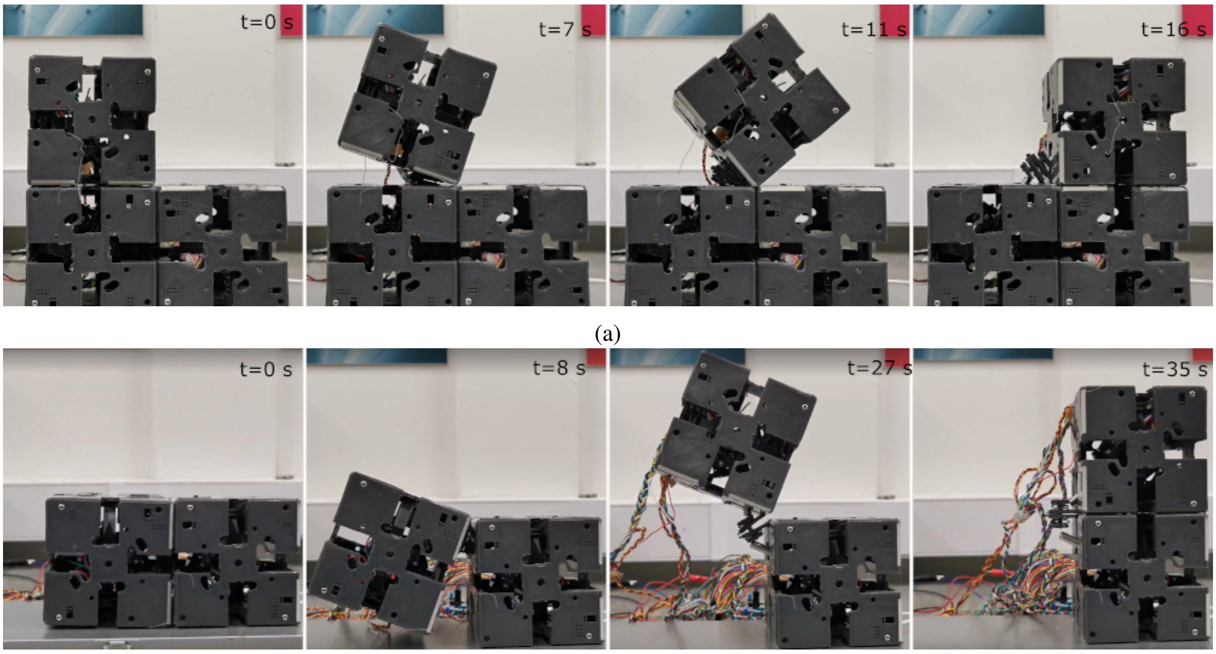
3D printed compression and torsion springs are integrated in the gates as well to decrease the number of parts to be assembled, see Fig. 6e. The compression spring retracts the backplate and the pin, and the torsion spring returns the gate when the leadscrew stops pushing the gate. The elastic response of these springs is tuned by tailoring printing orientation and thickness of the parts. In a similar fashion, the torsion spring is manufactured by printing together two adjacent gates joined by a compliant part made of TPU, see Fig. 6f. The combination of both gates and the compliant part makes that when the one gate is pushed, the compliant part is loaded as a spring, and when the gate is released the TPU part returns to its initial shape thus closing the gate. The base of the mobile magnets integrates a spring as well for two purposes: i) to keep in place the rotating part to be ready for docking; ii) to return the rotating part after the wedge in the gate backplate stops pushing it. To accomplish this, an embedded piece of TPU was printed in the rotating part, shown in white in Fig. 6g. A TPU section was also added in the arms of the rotating part to allow some compliance, and assure a good contact between the magnets even in presence of manufacturing tolerances.

For the actuation system, three 6V DC motors with a gear ratio of 380:1 (Pololu) were selected. A Hall-effect sensor is placed on each motor extended shaft to control its position. A trapezoidal 8 mm screw with a pitch of 2 mm was used for the leadscrew.

Finally, for the control system, the development board Nucleo-F767zi - based on the STM32F767 microcontroller - was selected. At this stage, the microcontroller is placed outside the module, but a custom-made PCB board will be manufactured to be fitted inside the module.

A set of experiments were performed to evaluate the moving and docking system. In the first experiment, shown in Fig. 7a, three modules were initially attached together, and then two modules were actuated to make the top module rotate by $\pi/2$. As shown in the figure, both gates push each other inducing rotation, while the pins integrated in the gates prevent slippage and maintain the rotating module in the correct position. At the end of the $\pi/2$ movement, the module achieves the desired position. This reconfiguration movement takes approximately 16 s.

For the second test, two modules were initially docked together in a horizontal position, see Fig. 7b. Then, both actuators were moved at the same speed to move the gates and successfully induce a π movement. Even though at some stages during reconfiguration the gates does not seem to be in full contact, the integrated pins allow to complete the movement with any problem. This movement takes approximately 35 s.



(a)

(b)

Fig. 7: Time-lapse of the experimental tests showing: (a) $\pi/2$ movement; (b) π movement.

V. CONCLUSIONS AND FUTURE WORK

In this work a new platform for modular construction and manufacturing has been proposed. It is envisaged that this and similar systems will eventually be part of a new form of manufacturing smart dynamic products. Key enabling aspects to realise this vision are addressed in the proposed design, in particular reconfiguration, docking and communication challenges. The experimental results show that the modules are able to reconfigure in 3D using only three actuators; this is a smaller number of actuators in comparison to most of the existing platforms capable of 3D reconfiguration. The time needed to complete reconfiguration can be easily tailored by changing the pitch of the leadscrew or the speed of the motors. Furthermore, the docking force is large enough for one module to withstand the weight of another one in a horizontal chain. In addition, the approach of using embedded 3D-printed springs reduces the number of parts and this translates into faster assembly. Further developments include embedding the microcontroller inside the modules and integrate sensors like IMUs for the orientation and strain gauges to measure the forces applied at the docking sites, with the aim of increasing autonomy and adding more functionalities to the platform. Reduction in size would also be an interesting avenue of research to increase the range and ”surface finish” of the structures composed of the modules.

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