RoFICoM – First Open-Hardware Connector for Metamorphic Robots

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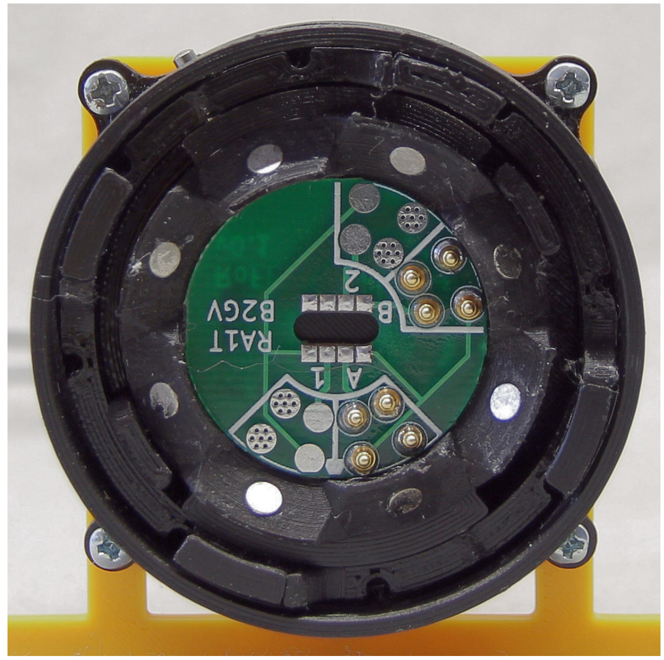
***Abstract*— We present RoFICoM, a new retractable connection device that allows for mechanical, electric, and data communication connection between separable robotic modules. The device is intentionally designed to be used in lattice-type metamorphic robots, however, its applicability is much wider. The main novelty of our solution lies primarily in a new unique flat design and spatial compactness of the connector. With a flat connector, much more space is left for the body of a robotic module in the structure. Moreover, the connector is also fully self-contained device with well defined mechanical, electrical and data interfaces, hence it can be easily embedded in various robotic solutions. Our RoFICoM connector is easy to produce, it is open-hardware and free for non-commercial use. In the paper, we give construction details and report on a couple of experiments we performed to demonstrate key features of the connection achieved with two RoFICoM devices.**

I. INTRODUCTION

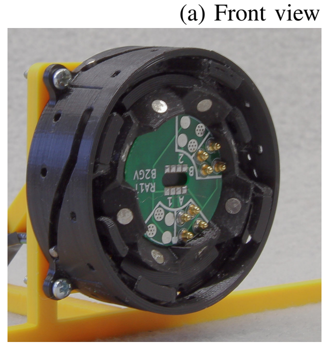
Modular self-reconfigurable robots provide a fault-tolerant, adaptable and versatile solution to a plethora of specific tasks to be performed in diverse and versatile environments. Individual modules of such a system contain various sensors and actuators and may connect together in multiple topologies in order to form a robot with a shape required by a concrete task. For example, in a lattice-based [1] reconfigurable robotic system, a robot may take the form of a worm in order to pass through a narrow place, and once it gets through, it may reshape into e.g. a spider-like configuration to start moving faster towards its final destination.

The crucial element of modular self-reconfigurable robots is the way in which individual modules are connected and disconnected. The characteristics of the connection mechanism prescribe the overall qualities of the reconfigurable system. Clearly, the higher is the reliability of the connection of two disconnected modules, the higher speed of reconfiguration the whole system may achieve. The mechanical strength of the connector limits the size and dynamics of the system; gendered and asymmetrical connectors naturally restrict the number of possible connections. The connectors can provide communication and power channels and hence dictate the form of inter-module communication and their power management. Finally, the size and spatial compactness of the connector itself is a limiting factor in terms of module miniaturization.

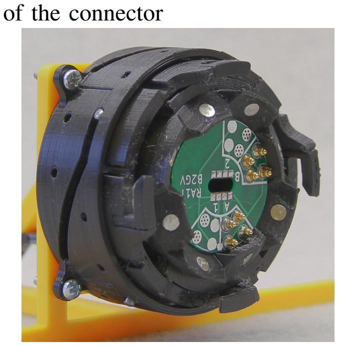
We present a new connection mechanism – the RoFI Connection Mechanism, RoFICoM for short, on top of which we intend to build modular robotic kit. RoFICoM is an open-hardware genderless 90-degree symmetric connection mechanism for modular robots, see Figure 1. It can establish a firm mechanical, data and power connection between two modules without any a priori synchronization. The connector is suitable for densely occupied grid-based (lattice-type) systems as it expands when connecting and retracts when disconnecting. Therefore, the connector does not block adjacent modules movement. The novelty of our connection mechanism lies in a full encapsulation and a new flattest design so far which is optimized for consumer-grade desktop 3D printing. The full encapsulation means that the connector is not an integral part of the robotic module, hence users may treat RoFICoMs as black boxes and quickly integrate



(a) Front view of the connector



(b) Unconnected



(c) Connected

Fig. 1: The RoFICoM connector

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them into their designs. As a standalone component, the connector provides mechanical and electrical coupling via which the connectors can share power and exchange data on the outer side of the connector. On the inner side, the connector exposes an SPI slave interface to be connected to the robotic module.

II. Related Work

There are a couple of projects dealing with design and realization of modular self-reconfigurable robots [3], [2], [8], [9]. Unfortunately, these systems usually cannot be bought, neither can users build them on their own easily. Since the systems are unreachable to the general public, they cannot reach their full potential, and the robotic community cannot benefit from and build on top of them.

As for the connection mechanism used in reconfigurable robotic systems, Wael Saab et al. [6] present an exhaustive summary of the advances in the design of the connection mechanisms for the last three decades. The designs usually use mechanical (latches, pins with matching holes) and electro-magnetical (electro or electro-permanent magnetic) principles to connect the modules.

Our solution is closely related to the HiGen connector [4]. Similarly to RoFICoM, HiGen is a genderless, 90-degree symmetrical connector with data and power lines. The HiGen connector relies on mechanical latches to establish a firm mechanical connection. It is retracted in the disconnected state and therefore movement of modules in dense lattice structures is not restricted. HiGen is the first connector combining all the features in a single device. The connector also does not require any synchronization for the connection, hence a module can release the connection without the co-operation of the mating side. The authors used the connector in the HyMod module [5] where the connector seems to be an integral part of the robot. The connector was 3D printed; however, the drawings and CAD models are confidential.

Example of a self-contained connector is EP-FACE [8] from the SMORES project [2]. It is an electro-permanent magnet based, hermaphroditic, 90-degree symmetrical solution. EP-FACE features no data nor power lines. The connector can connect and disconnect in order of tenths of milliseconds due to the magnetical principal of operation. However, both mating sides have to cooperate on releasing of the connection. EP-FACE is a stand-alone unit controlled over an I2C bus.

III. Implementation

The RoFICoM connector is a cylindrical object measuring 50 mm in diameter, with a depth of 17 mm, in the disconnected state. There are four M2 mounting holes around its perimeter. The mechanism consists of five 3D printed PLA plastic components, two PCBs (mechanical contacts and the control circuitry) and some fasteners. A single small geared N20 DC motor housed directly in the body of the connector drives the whole mechanism.

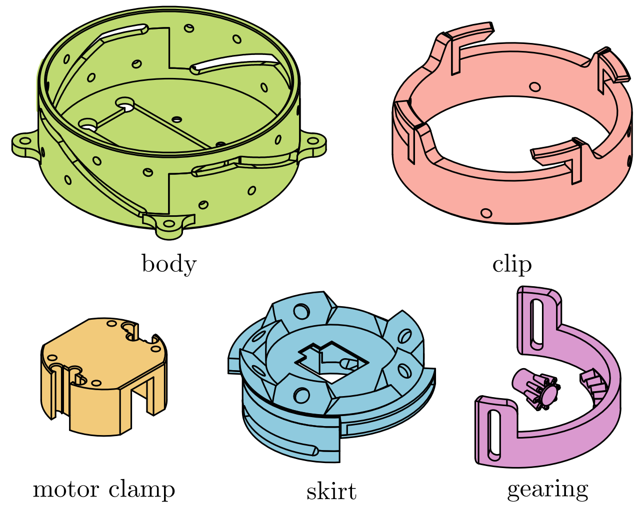


Fig. 2: The components of the connector

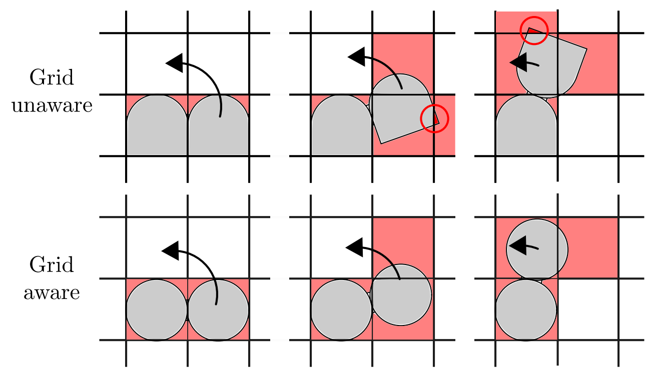
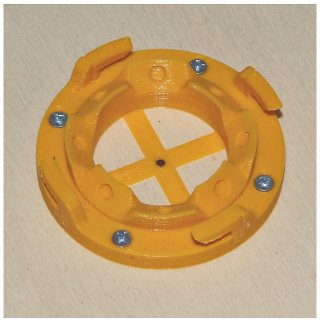


Fig. 3: Illustration of grid awareness. If a double cell modules tries to move one of it bodies from right to top, grid-unaware module occupies extra cells of the grid.

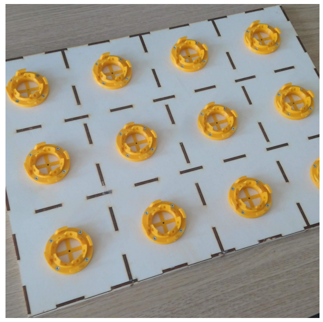
A. Mechanical Details

Likewise the HiGen connector [4], there are four hooks attached to a ring (named clip, see Figure 2). The motor rotates the clip, which then slides out of the body using pins driven by a helical slot in the body. The hooks slide under hooks in the mating clip and therefore, prevent the connectors from being pulled apart. However, the hooks itself are not sufficient for a mechanical connection as mutual rotation of the connectors releases the connection. To prevent that, another component, skirt, is extended together with the clip. The skirt is blocked from rotation using a slot in the body. When two skirts face each other, they prevent the connector from rotation against each other. The combination of the two restrictions of freedom forms a firm, mechanical connection.

If the modules of the system can form regular lattice-type structures, it can be considered an advantage not to occupy the whole cube cell of the grid by a module. Instead, only if the module occupies sphere inscribed in the cell, the modules do not block movement of adjacent modules (see Figure 3) – they are *grid-aware*. However, grid-aware modules

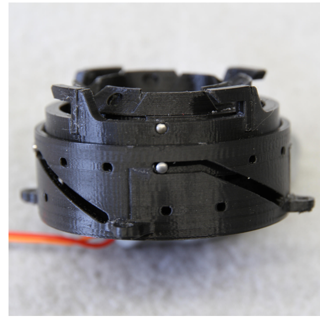


(a) Passive connector

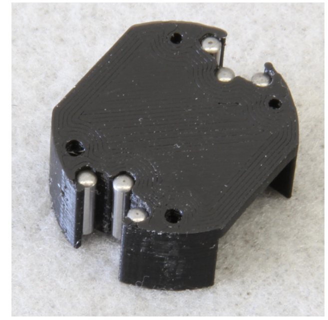


(b) Passive plate

Fig. 4: Usage of passive elements



(a) Pin driven in slot



(b) Guide rail

Fig. 5: Usage of the steel pins

feature only a point contact between modules, which is not enough for establishing a firm mechanical connection. This problem is solved by making the connection mechanism extendable, i.e. for the connection, the mechanism extends towards the connection plain. Also, both, clip and skirt, are 90-degree symmetrical and therefore, the docks can connect in four orientations. These features enable more versatile configurations and reconfiguration options for the systems.

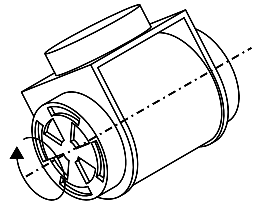
The connection features another useful property – the connectors require no cooperation for establishing the connection. Therefore, the modules do not have to perform precisely synchronized movements when connecting. The absence of synchronization simplifies implementation of the connection. Also, faulty units can be disconnected from the system without their cooperation. Moreover, it is possible to build a passive connector (see Figure 4a) – a component with no moving parts to which another connector can connect. Having a passive connector is beneficial as it allows to construct two items: entirely passive modules (e.g., wheels, battery packs or chargers), and surfaces which the modules can easily attach to and move on. Roombots [7] heavily rely on passive components and have demonstrated their usefulness. We have successfully manufactured the passive surfaces (see Figure 4b) by cutting the baseboard using a laser cutter and screwing 3D printed passive connectors to it. Using the plywood or acrylic baseboard significantly speeds up the manufacturing compared to a fully 3D printed solution.

One of our requirements for the design of the connector is easy and widely accessible manufacturability. We decided to use FDM 3D printed plastic components as there are already commonly available desktop 3D printers, which yield decent quality components. However, 3D printing technology comes with its limitations – it cannot produce arbitrary components. The main limitation is a rather poor surface finish compared to traditional processes such as milling, varying precision (important for appropriate fitting), minimal feature size, and the problematic manufacturing of components with overhangs.

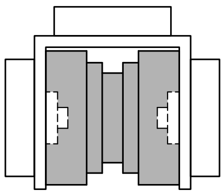
The reduced surface finish quality on an FDM 3D printers is caused by depositing layer-by-layer which leads to small bumps. These bumps prevent components from smoothly sliding on each other, and they can lead to jamming of the mechanism, hence its unreliability. Note that this is only a problem for vertical surfaces and slopes, the horizontal surfaces provide a decent finish. The similar problem is with varying precision of the 3D printed components in the order of hundredths of millimeter where it is hard to achieve the desired component fit without additional clearances repeatedly. It is possible to mitigate the problem with manual post-processing (e.g., sanding); however, this increases manufacturing cost and time significantly.

To avoid these issues in our connector, we designed it in a way that prevents any 3D printed component to 3D printed component contact. Instead, we leverage the standard steel cylindrical hardened pins (DIN6325). We use them for two purposes in our design – first, they drive clip in the helical slot (see Figure 5a), second, they serve as a guide rail in a slot preventing the skirt from the rotation (see Figure 5b). Their smooth surface slides well on the 3D printed surface and therefore, allows for jam-less operation. Additionally, we use plastic spacers to provide clearance between the body and the clip to prevent two 3D printed surfaces from sliding against each other. Usage of the pins allows us to skip any manual deburring or sanding of the surfaces and therefore, to significantly lower the assembly time.

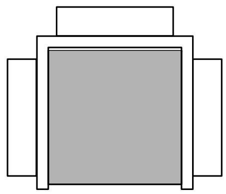
Another challenge for the design is to overcome the limited possibility of overhangs in the components. 3D printers can produce components with overhangs by printing support structure underneath. However, this structure has to be manually removed, and additionally, the overhanging face loses its precision and surface finish – therefore, it is not usable as a functional surface. Alternatively, the support material can be water soluble, which easies the removal, though, multi-material printers are not yet widespread. For our design, this is the case of hooks on the clip and slots in the body and skirt. We, therefore, split the components with overhangs into several bodies such that there are no overhangs in them. Then, the bodies are glued or screwed into the desired component. This optimization allows us to produce functional overhanging features and further reduce the time and difficulty of assembly. We print our components out of PLA, and we glue them using cyanoacrylate glue. Our experiments in Section IV show that the glued joints



(a) Example module with one degree of freedom



(b) HiGen usable space



(c) RoFICoM usable space

Fig. 6: Comparison of usable body space (gray) of an example module for the HiGen and RoFICoM connectors

are not the weakest points – bonding between layers of the 3D printed component is weaker than the glued joints.

RoFICoM features a flat design with no components sticking out of the body (e.g., motors, limit switches) compared to the existing solutions – RoFICom has a uniform depth of 17 mm. For comparison; HiGen maximal depth is 35 mm, EP-FACE depth is 16 mm. However, EP-FACE is not expandable. Therefore, it is not suitable for grid-aware modules.

We designed RoFICoM with a diameter of 50 mm, however, it can be arbitrarily extended while preserving constant depth. Also, the amount of retraction can be parametrized, however, with some impact on the overall depth of the connector. For the given retractable distance e, diameter d of used steel pins, and wall thickness t (1.5 mm in our case), the depth of the whole connector is $e + d + 6t$.

The flatness of the dock is a great advantage as it preserves more usable body space in the modules. Consider a module with similar topology to HyMod [5] – a module inscribed in a sphere with a diameter of 140 mm. The module features one degree of freedom, which allows the module to rotate a U-shaped piece with three connectors on it around its body – see Figure 6a. The whole sphere has a volume of 1437 cm^3. In the case of HiGen connector, the maximum usable body space has a volume of 393 cm^3 (Figure 6b). If we exchange the dock for RoFICoM with a diameter of 70 mm, the usable volume increases to 488 cm^3 (Figure 6c) which is a 24% increase. Also, in the case of RoFICoM, the body shape is a simple cylinder without an inconvenient cutout that is present in the case of HiGen. The cutout further restricts practically usable space as it can, e.g., limit the size of the motor placed in the module. Usage of RoFICoM also allows for shrinking down the module size – the presented size of 50 mm is suitable for modules with a grid size of 100 mm.

To achieve the flattest design among currently available solutions, we swapped the arrangement of the skirt and the clip compared to HiGen – the clip is the outer ring, the skirt is the inner one. The swap allowed us to lay the motor flat and save connector depth (see Figure 7). The motor drivers the mechanism using a simple bevel gearing. The gearing is 3D printed as no suitable gearing with appropriate size cannot be simply and cheaply sourced. We used a cycloidal tooth profile instead of a standard involute one, as the tooth profile is more massive and more suitable for 3D print.

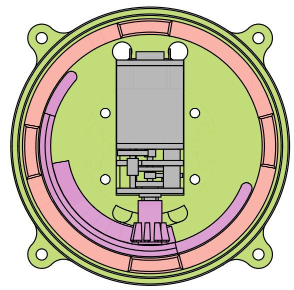


Fig. 7: Internal arrangement of the connector – top view without skirt. The motor is shown gray.

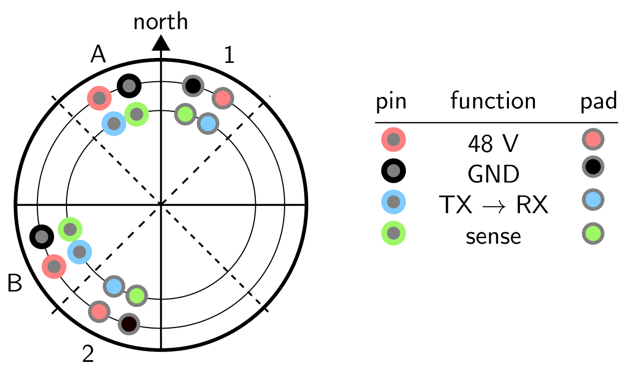


Fig. 8: Skirt pins arrangement allowing for 90-degree symmetric connection

Changing the arrangement of the components also provides a wider base for the extendable components of the dock compared to the HiGen, and therefore, RoFICom could be more rigid, especially under the tangential stress. However, as we could not obtain a physical copy of HiGen, we did not verify this conjecture.

B. Electrical & Communication Details

The skirt of the module carries a small PCB with several spring-loaded contacts and pads (see Figure 8), which allows the connecting modules to communicate, share power and to detect their mutual orientation via the sense pin. The spring-loaded contacts can transfer 2 A of current each; they are in a single configuration for the data lines and doubled for the power-sharing lines.

The connectors communicate using high-baud rate UART over a custom protocol. The protocol is rather simple and allows the connectors exchange merely binary blobs that remain uninterpreted by the connectors itself.

The ability to pass arbitrary binary blobs to the mating

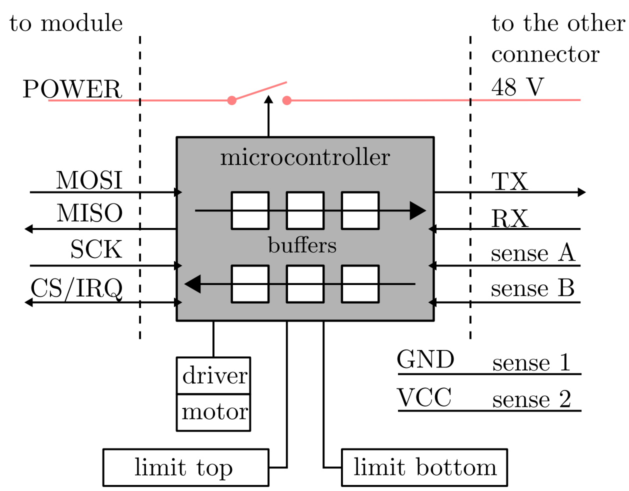


Fig. 9: Block diagram of the connector.

connector allows the user to build a custom communication protocol or adapt an existing one. Our setup can also serve as a custom L2/L1 of the standard TCP/IP stack. We have successfully implemented a driver for our connector compatible with the lwIP TCP/IP stack and verified that establishing standard TCP/IP is possible. We see the usage of the TCP/IP as a primary communication channel among the modules as an advantage. With the standard TCP/IP most of the existing software solutions including the state-of-the-art achievements can be reused. Also, with the standard TCP/IP the robotic modules may seamlessly integrate with existing networks and need not treat wired and wireless communication differently.

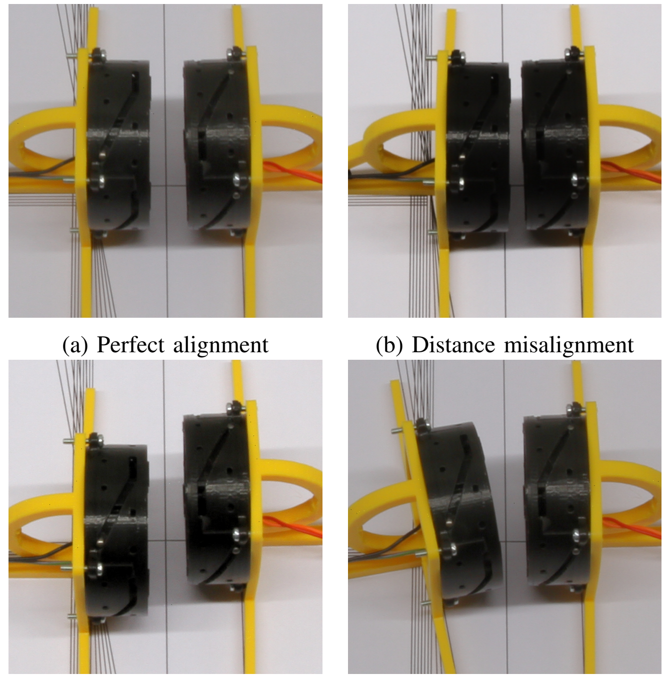
The connector can switch the power lines using power MOSFETs. The controllable switching prevents arcing during connection, which shortens the lifetime of the spring contacts, and also allows the module to choose whether to participate in power-sharing.

The connector is controlled using an STM32 microcontroller hosted on a PCB serving as the back face of the connector body. The DC motor is driven by an H-bridge, and its position is sensed using hall sensors and small magnets placed in the 3D printed components. See Figure 9 for a block diagram of the connector.

IV. Experimental Evaluation

In order to evaluate our connector, we run several experiments. We tested connection repeatability, measured the forgiveness area and the load capacity under various conditions. A video showing the RoFICoM in action is included in the supplementary materials.

All the experiments were conducted on units printed out of PLA with the layer height of 0.1 mm. The motors were powered by 7.4 V in order to emulate nominal voltage of 2-cell Li-ion accumulator pack. To conduct the tests, we 3D printed mounts for the connectors which allow them to stand vertically and also allows us to apply a load on their back faces via a carabiner.



(a) Perfect alignment (b) Distance misalignment

(c) Parallel misalignment (d) Rotation misalignment

Fig. 10: Test setup showing various misalignments

A. Connection Repeatability and Area of Acceptance

We printed a paper template with guiding lines which allowed us to arrange the connectors in various misalignment (see Figure 10). We tested distance, parallel, and rotational misalignments. During the experiment, one of the connectors was rigidly secured in its position; the other one was secured by a weight placed on the mount to be allowed to move if the force built was large enough. The ability of movement reflects the planned usage where the connectors can be slightly misaligned but the system does not prevent from pulling it into the correct position.

We run the experiment as follows: the connectors were placed into the initial position, then both connectors were activated, and the result was observed. After the trial, the connectors were again put into the initial position. We repeated the procedure with various initial configurations; each configuration was run 20 times. The results are summarized in Table I.

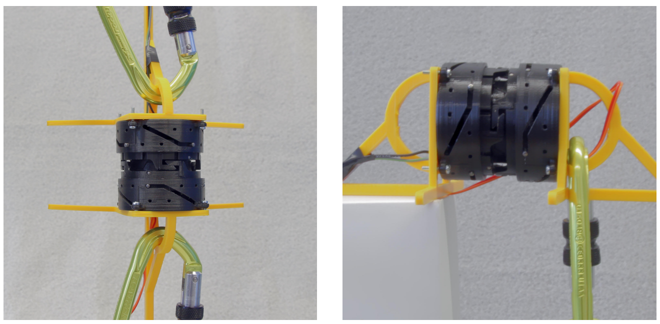
Additionally, we performed a test for connection repeatability – we connected the connectors and then repeatedly disconnected them and connected them again. When the connection was unsuccessful, we reset the experiment. We repeated the experiment 20 times and limited each run to 50 connection. 17 of the runs were completed successfully, the rest failed after 26, 30 and 42 reconnections.

B. Connection Strength

We measured the connection strength by attaching weights to the connected connectors. We measured the load capacity in two directions: normal (Figure 11a) and shear (Figure 11b). We were able to attach 11.5 kg of the load

Displacement Type	Amount	Success Rate
None		20/20
Distance	-6 mm	14/20
	-4 mm	16/20
	-2 mm	20/20
	$+2$ mm	19/20
	$+4$ mm	10/20
	$+6$ mm	1/20
Parallel	1 mm	20/20
	2 mm	20/20
	4 mm	17/20
	6 mm	9/20
Rotation	$2°$	20/20
	$4°$	19/20
	$6°$	19/20
	$8°$	18/20
	$10°$	14/20

TABLE I: Area of acceptance experiments results. See Figure 10 for illustration of the displacement types.



(a) Normal load (b) Shear load

Fig. 11: Test setup for measuring load capacity

in the normal direction and 5.4 kg in the shear direction until the connection released. In both cases, the disconnection leads to breaking the hooks on the clip. To our surprise, the hooks broke between 3D printed layers rather than between two glued surfaces. Therefore, we consider gluing 3D components as a viable way of producing overhangs in our design.

The performance of RoFICoM is incomparable to HiGen as the authors measured load only up to 2 kg and only in the normal direction. The performance of RoFICoM is similar to the performance of EP-FACE. We also think we could further improve the load capacity of RoFICoM by optimizing the hooks as they are the weakest point.

Finally, we measured how much weight can the connector lift. This is important in the case when the whole system is lying on the connector and the connector is supposed to expand. We measured it by facing the connector on a horizontal surface and placing a weight on top of it. The connector was able to lift 1.4 kg in our prototype implementation.

V. Conclusions

We present an improved and open alternative to the HiGen connector to be used in lattice-type modular reconfigurable robots. Compared to HiGen solution [4], our connector is significantly more spatially compact while preserving competitive connection parameters. Moreover, the RoFICoM design is highly independent of a concrete robotic platform and is out-of-box ready to be integrated into various robotic projects. The fixed mounting holes on the body, self-continedness and fixed communication protocols allow users to integrate the connector in their modules and also provides them with the possibility of upgrading to a newer connector version as a drop-in replacement.

We have chosen TCP/IP as a primary communication protocol between RoFICoM equipped modules which open the possibility of seamless inter-operation of modular robots and existing network services. We have demonstrated the feasibility of such the solution using two RoFICoM equipped modules.

Our project is open to the public, therefore, all the source-codes, 3D models, construction manuals, etc., are freely downloadable from our project website `https://rofi.fi.muni.cz/`. In the future, we intend to design the whole open-source and open-hardware reconfigurable robotic system on top of the RoFICoM connectors.

VI. Acknowledgement

This research was supported by ERDF "CyberSecurity, CyberCrime and Critical Information Infrastructures Center of Excellence" (No. CZ.02.1.01/0.0/0.0/16 019/0000822).

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