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Hyblock: Hardware Realization and Control of Modular Hydraulic Robots with Dowel Connectors

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Abstract— **This paper presents the hardware design and development of Hyblock, a modular hydraulic robot for heavy-duty application such as construction. The robot is equipped with a simple docking mechanism called a C-type expansion dowel and a novel hydraulic circuit MHSB that matches the modular structure. In this paper, we first report on the design of the robot hardware including the dowel and hydraulic circuit, then present preliminary experiments on pressure-based torque control and docking control using proximal magnetic sensors. Next, we propose a framework for dynamic reconfiguration and task-space motion control built on the concept of dowel connectors. Simulation results demonstrate that a collective modular robot achieves desired motion tasks while keeping all normal contact forces of the connectors being lower-bound. The results are also explained in the supplementary video.**

I. Introduction

Considering the current socio-economic and natural environment, there is a growing demand for robots capable of operating in locations essentially inaccessible to humans, including agriculture, forestry, fisheries, civil engineering, construction, logistics, infrastructure maintenance, and disaster response. There is a pressing need for innovative robot solutions that can adapt to the aforementioned demands while also minimizing manufacturing and operational costs.

However, most existing heavy-duty machinery for construction application, such as excavators, bulldozers, and cranes, have mechanical and control architecture that is specific to each respective task. They are generally difficult to relocate quickly (because of size and weight), but often occupy large parking spaces in each region without being used. Their high durability and the long service life paradoxically engenders toleration of their low utilization rates.

We believe that the *Modular Hydraulic Robots* solves the difficulties presented above. In the academic realm, there are well-known research fields such as reconfigurable robots or self-organized robots. Pioneering research, led by Fukuda [1], has been followed by the proposal of various concepts [2], mechanisms [3], and algorithms [4]. The reader is recommended to see a survey paper, e.g. [6]. These can be defined as an intelligent robotic systems in which independently moving monofunctional robots come together to flexibly achieve a common task objective as a collective, adapting their shapes to irregular environments. It is believed the modular systems offer numerous advantages throughout all phases, including design, manufacturing, operation, disposal, mobility, portability, redundancy (in case of failure), maintenance, and reuse.

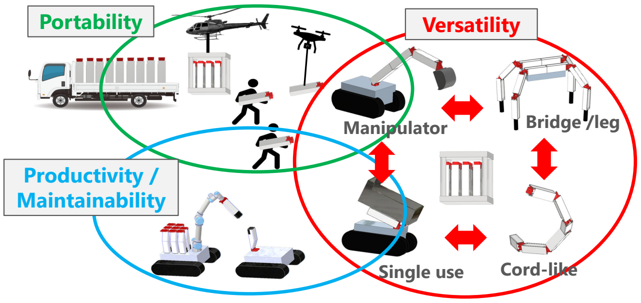

Fig. 1. Modular hydraulic robots for heavy-duty application

However, there are few instances of modular robots capable of executing heavy-duty tasks across diverse ground-based environments, as outlined in the introduction. We attribute this limitation primarily to the strength of the actuators employed. Therefore, the authors have directed their research toward hydraulic drive systems, with the goal of creating a modular robot suitable for heavy-duty applications, as depicted in Fig. 1. In our endeavors, we prioritize the prompt development of hardware over the attainment of autonomous systems through some state-of-the-art artificial intelligence tools [7], under provision of domestic/international collaborations.

Our emphasis lies in maximizing the inherent robustness and high power characteristics of hydraulics, as well as harnessing the smart power distribution capabilities offered by hydraulic circuits during on-site operations. In the context of modular robotics, several advantages of hydraulic systems can be highlighted:

(H1) Highly resistant to impacts, suitable for all-weather conditions, and cost-effective [8].
(H2) Possible to achieve significant force with compact motors and pumps, albeit at the expense of reduced speed.
(H3) Capable of monitoring and controlling forces through pressure.

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- (H4) Hydraulic power can be utilized for active docking and release of the connectors.
- (H5) Actuator motion can be easily locked by using non-leakage valves.
- (H6) Power can be transferred between axes through pressure boosting and flow-summing [9].

This paper presents our attempt toward realization of modular hydraulic robots addressing three major subjects:

- (S1) Simple and reliable connector mechanisms
- (S2) Method of hydraulic power supply to the modules
- (S3) Automatic reconfiguration and control framework

S1 is important because heavy-duty modules cannot be assembled easily by human effort. Sloppy assembly can engender severe accidents. The connector mechanisms with high force capacity have been studied intensively in space applications [10], but they are too complex and large to be applied to low-cost robots. See [11] for a survey. S2 is a unique issue for hydraulic modular robots. Its technical difficulty derives from "separation" of the power supply because of the disassembled modular structure. S3 is widely studied mainly by the researchers in computer science. Recently, many authors proposed planning-based [12], or learning-based algorithms [7], [13].

Our current trial is subject-wise, and not fully integrated so far. Nevertheless, this first report shows an important technical milestone. In the following, Section II describes the mechanical hardware design. Important focus is block-like (monocoque) design and the associated dowel connectors adopted in the second prototype (S1). Then, Section III reports a progress of the new modular hydraulic circuit under development (S2). A new co-axial hydraulic coupling is also presented. Section IV presents an idea of reconfiguration and control built upon the dowel connector concept (S3), followed by a simulation result, where the modular collectives achieve some motion control tasks while maintaining the constraint forces. The experimental movies are provided as the supplemental file.

II. HARDWARE REALIZATION OF MODULAR HYDRAULIC ROBOT; HYBLOCK

A. Robot structure

Since this project has launched in 2018, several prototypes have been developed, primarily driven by small, lightweight hydraulic cylinders and servo valves, designed to be portable by a single person. These prototypes incorporate joint torque control based on pressure regulation, and are capable of compliant or rigid motion control.

Notably, the second prototype feature a monocoque structure devoid of external protrusions. Figure 2 shows the mechanical design. The outlook led us to call the robot "Hyblock". Multiple circular grooves are provided on the surface, and *C-shape expanding dowels*, explained below, has been invented for easy connection and disconnection of modules. The hydraulic cylinder barrel and pipelines are formed inside of the robot body as shown in Fig. 3.

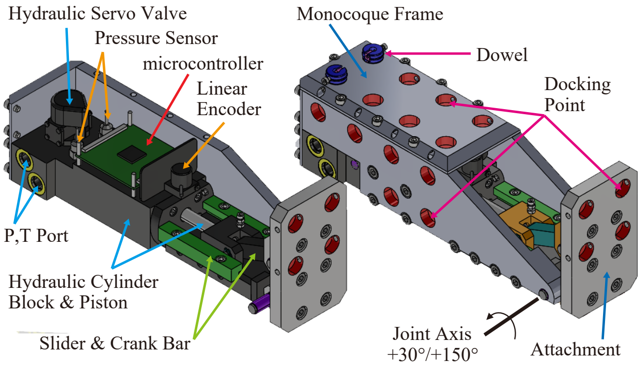

Fig. 2. Mechanical design of Hyblock-I

TABLE I
SPECIFICATIONS OF HYBLOCK-I

Dimensions	376 × 100 × 144 mm (L × W × H)
Weight	6.2 kg
Actuator	Single-ended cylinder (D25/d12.5) MOOG Type 30 Servo Valve (6.8 LPM)
Motion Range	−30°/+150°
Joint Power	Max Torque: 166 Nm (at 8 MPa), Max Speed: 1185 deg/s (at 8 LPM)
Sensors	Linear Encoder (MTL MLS-12-600E) Pressure Sensor (Toyo Sokki) x2
Power supply	24V DC
Controllers	NXP Semiconductors LPC4078 (onboard), 64bit WindowsPC (external)
Control Cycle	Task-level: 100 Hz, Servo-level: 2 kHz

The external connections consist of two hoses (pressure and tank), an electric power cable (24 VDC) and a communication cable (Ethernet). The main specifications are listed in Table I. The pressure can be increased up to 21 MPa, and the joint torque also triples. We have also developed a two-joint module as a variation. Figure 4 shows the experiment of docking with dowel and proximal sensors, which we describe in Section II-C.

B. C-shape dowel for module connection

The assembly of the connector is shown in Fig. 5. It consists of a C-shaped dowel, an A-shaped insert (wedge), and a bolt (hex head screw with a precisely measured unthreaded portion), and is assembled into a circular groove on the other side. The bolt serves to prevent the dowel from falling off when it loses friction.

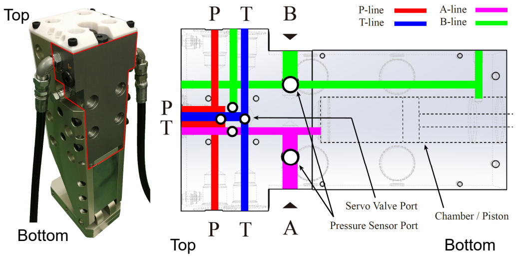

Fig. 3. Hydraulic path inside Hyblock-I

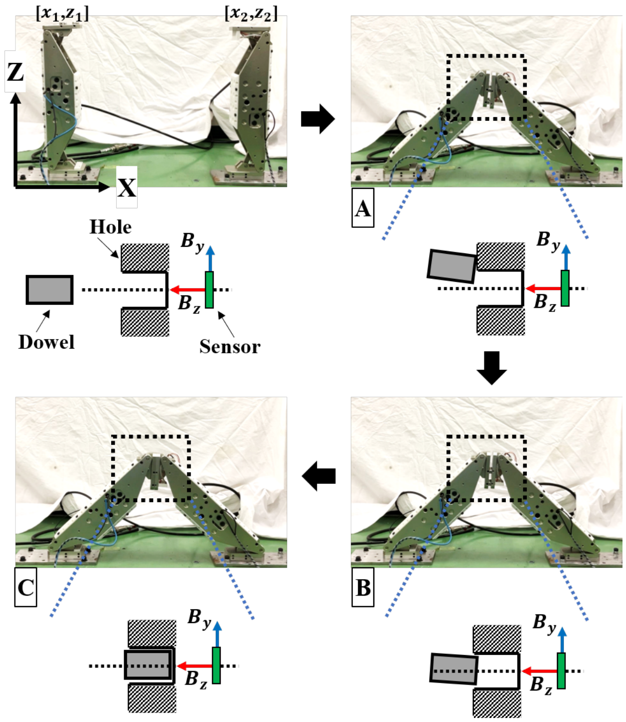

Fig. 4. Two-joint modules docking each other with dowels and proximal sensors (see supplemental video)

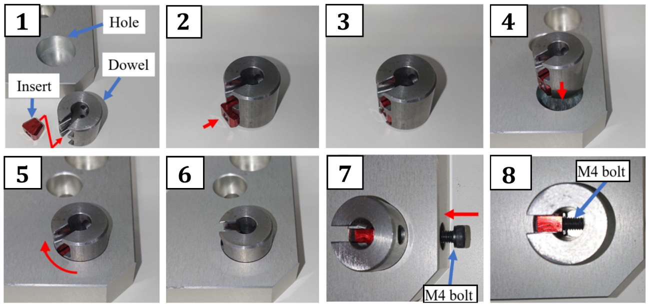

Fig. 5. Installation of C-shape expanding dowel into a metal plate

The C-shaped dowel has a diameter of 20 mm, a length of 20 mm, and is made of S45C steel. The theoretical value of the axial load capacity is approximately 400 N. The dowel-type connector employed in Hyblock facilitates the sensing and control over assembly and disassembly processes as follows.

C. Compliant docking using force control and proximal sensor

A preliminary experiments on assembly tasks using an electric manipulator are conducted as shown in Fig. 6. A plate imitating the docking surface of a modular robot is affixed to the force/torque sensors attached to the manipulator's tip. We assume mid-, long-distance position measurement could be achieved by some existing methods using lidar cameras.

Upon approaching a certain distance, the robot enters a "search mode" to identify the precise position of the docking surface by utilizing a magnet installed in the dowel body. We use an onboard magnetic proximity sensor (LIS3MDL 3-Axis Magnetometer by ST Micro Electronics) to detect the position and orientation of the magnet positions.

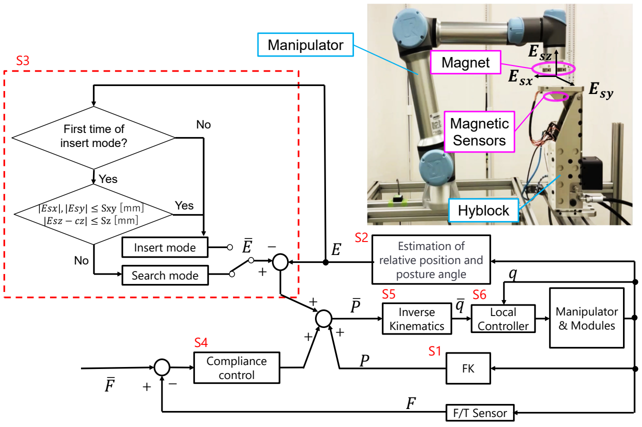

Fig. 6. Merging control by assembler manipulator with proximal sensing (see supplemental video)

When the two surfaces partially make contact, position errors are mitigated through force-controlled compliance. Since the clearance of the dowel is large enough (0.1 mm tolerance to 25 mm diameter) , the docking task is not difficult. However, additional work is required to tighten the screws in the dowels. This is a limitation we have to remove as the project progresses.

III. MODULAR HYDRAULIC CIRCUIT

A. MHSB

This section reviews our hydraulic drive circuit, designated as a *Modular Hydraulic Servo Booster* (MHSB), first presented in the literature [16]. The circuit diagram is depicted in Fig. 7, in which a manifold block has a servo-pump, check valve, switching valve, and internal hydraulic lines. The switching valve is a three-position, four-port valve, but one can replace it with multiple two-port valves or custom-made three-port valves. The hydraulic lines are P (common pressure), T (tank), S (shared) , and Outlet/Return line. The Outlet/Return line is connected to servo-valves.

The circuit is designed to seamlessly transit, according to the robot's motion and load conditions, between five modes; 'N (normal) mode' operated by an external HPU, 'DB (decoupled boost) mode' powered by an internal sub-pump, 'SB (shared boost) mode' utilizing flow rate shared with other modules, 'AB (assist boost) mode' to devote its all flow to other modules, and 'PTO (power-take-off) mode' operating solely by devoted flow.

While the effectiveness of the hydraulic circuit has been tested through real-world experiments in the literature [16], the circuit was constructed by combining various components from laboratory stock. Now we designed

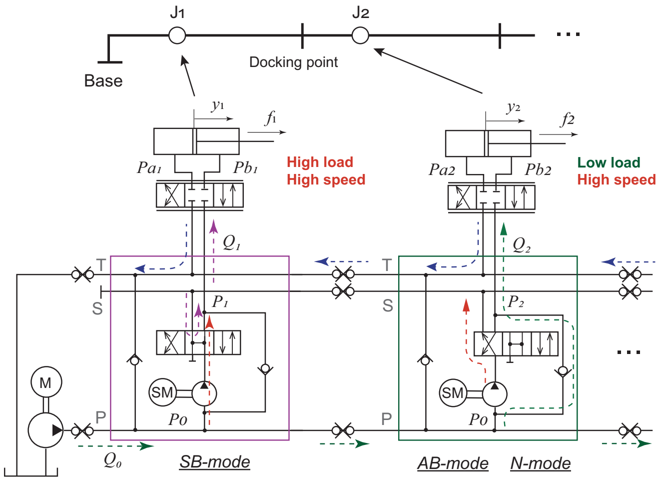

Fig. 7. Multiple MHSB units distributed to serially configured modular robots. The figure shows a situation in which the first module is SB-mode, whereas the second is AB/N-mode.

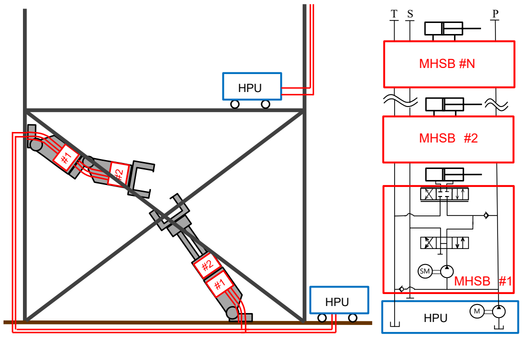

Fig. 8. Illustration of hydraulic pipeline over distributed modular collectivesdeployed to a construction site.

a block incorporating all the functionalities of the MHSB, allowing for easy attachment and detachment from the robot body, akin to a cartridge. Details are presented at the conference.

Because of the built-in pump, there is no need for an external HPU, allowing the modular robot to operate autonomously, as long as electric power is supplied. The single module may be utilized as a powered jack or an expander for emergency or outdoor applications. However, an external (portable) HPU is useful for rapid motion control (with N-mode) in construction tasks. It helps with the heat / contamination control of the whole system as well. Fig. 8 shows an illustration of hydraulic pipeline over distributed modular collectivesdeployed to a construction site. Note that rotary swivels or flexible hoses are installed at each joint.

B. Coaxial hydraulic coupler

A special coaxial coupler was designed to realize hydraulic piping between modular robots. Th coaxial coupler, located at the center of the contact surface, allows the surfaces between robots to be oriented in any direction.

The cad design is presented in Fig. 9. It consists of two coupler, one with an O-ring and the other not. The ball in the center and the two rings on the same axis are spring-loaded, and serve as lids to prevent oil from leaking out from the P, T, and S ports. When merged, they are pushed in, and the hydraulic lines between the modules are connected at the same time. Design of new connector mechanism compatible to the hydraulic coupler is also ongoing, where we try to solve any fluid leakage and contamination during reconfiguration.

IV. PLANNING AND CONTROL

A. Planning of structure and allocation

When deploying robots in a work environment for the first time, it is essential to solve the problem of where and in what order to assemble them. Furthermore, as the work progresses, the situation can change rapidly, necessitating the adjustment of the work plan in real-time (accompanied by the problem of configuring a limited number of pick-and-place or assembler robots). In other words, the dynamic reconfiguration of modular robots can be viewed as a composite problem involving optimal structural determination and allocation.

When the structure of the robot is fixed, optimal allocation becomes a relatively straightforward geometric planning task. However, the shape of the robot depends on the control tasks, making its determination challenging. Recently, optimal configuration and control problem with multiple manipulators or modular robots is studied by some authors [18], [19]. Existing literature, such as [7], has proposed rich frameworks that alternate between optimal shape exploration and optimal control by utilizing reinforcement learning algorithms.

Under limited conditions (especially when the variety of available parts is severely restricted), we implemented a heuristic graph search algorithm proposed in [12]. This algorithm, as depicted in Fig. 10, takes input in the form of parts and spatial trajectories and outputs the feasible robot structure. There is a trade-off between constraint stability and the number of modules mobilized, making the design of an appropriate cost functions of optimization challenging.

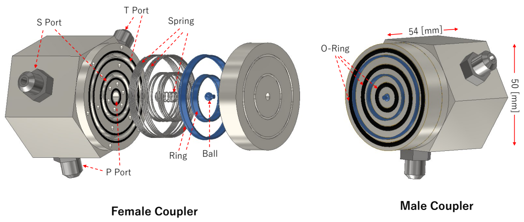

Fig. 9. Coaxial coupler was designed to connect three hydraulic lines between MHSB unit in each module.

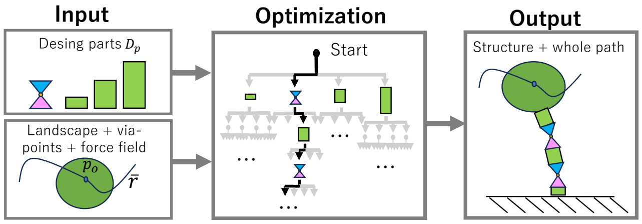

Fig. 10. Graph-based structural optimization inspired from [12].

B. Collective motion control upon constraints of connectors

Once the structure and allocation have been determined, each module must be controlled cooperatively. Consider an example of transporting an object within a given workspace, while ensuring avoidance of singular configurations. For conventional robotic systems like those with multi-fingered hands, constructing a force closure around the object is fundamental.

In the case of modular robots, the challenge is not only to establish a force closure around the object but also to maintain constraint on "all" contact surfaces between the modules. In other words, maintaining the mechanical structure is a high priority task over other motion tasks.

However, since the automatic dowel connection is yet solved, in this study, we propose an interim solution. Specifically, we merely rely on the forces generated by the actuators so that the modules push against each other, maintaining the overall structure while performing tasks. It leverages the characteristic of hydraulic actuators, which can easily exert significant forces in static situations.

Fortunately, in cases involving connections via two or more dowels as in Hyblock, the available degrees of freedom are limited to motion along the normal direction of the constraint surface. Consequently, the problem can be reduced to an inequality condition on the normal forces only. This makes the control problem compact. In this report, we utilize a priority-based, sequentially-quadratic programming proposed in [17] for whole-body motion control, which is explained below.

C. Control of collective modular robots within the force constrains on dowel connectors

Let us consider a simple object (identified as 'O' symbol) handling example as defined in Fig. 11. The superscript of each symbol in the figure denotes the tree (arm) number, while the subscript indicates the module number that comprises the tree. In this context, a module is assumed to consist of two links (triangular shape) and one rotational joint, identified by the symbols 'B' for the base link and 'E' for the end-effector link. These subscripts are temporal, and subject to change dynamically change according to the work situation.

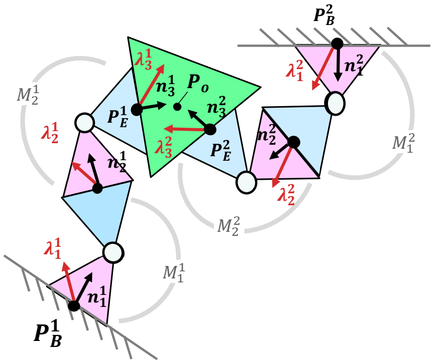

Fig. 11. Model definition: The green triangle in the center is a cargo, and the pair of pink and blue triangles represent one single-joint module. Projection of contact forces $\boldsymbol{\lambda}$ to the normal direction $\boldsymbol{n}$ must be bounded from below to maintain the structure.

Each module features two contact ends, with their representative points denoted by black circles. The generalized coordinates $\boldsymbol{q}$ are defined as the positions of the centers of gravity for each rigid link such as x_{1E}^1 or z_{1E}^1, and the absolute orientation such as ϕ_{1E}^1. Then, we can express the equations of motion by differential algebraic equations

$$\begin{bmatrix} \boldsymbol{M} & \boldsymbol{E}^{\mathrm{T}} & \boldsymbol{A} \\ \boldsymbol{E} & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{q}} \\ \boldsymbol{\lambda} \\ \boldsymbol{u} \end{bmatrix} = \begin{bmatrix} -\boldsymbol{H}-\boldsymbol{G} \\ -\boldsymbol{\gamma} \end{bmatrix} \tag{1}$$

where, $\boldsymbol{G}$ represents the gravitational term, $\boldsymbol{H}$ represents the velocity-squared term (absent in the planar model), $\boldsymbol{A}$ represents the actuation matrix, and $\boldsymbol{E}$ represents the Jacobian matrix of the left-hand side of the constraint conditions $\boldsymbol{\Phi}(\boldsymbol{q}) = \boldsymbol{0}$, which combines the pin constraints of the joints and the active dowel couplings, with $\boldsymbol{\gamma} = \dot{\boldsymbol{E}}\dot{\boldsymbol{q}}$.

Furthermore, $\boldsymbol{u}$ represents the actuator drive forces, and $\boldsymbol{\lambda}$ represents the constraint forces, both of which are crucial quantities to monitor during operation. Within $\boldsymbol{\lambda}$, we differentiate the dowel constraint forces as $\boldsymbol{\lambda}_E$ and the joint constraint forces as $\boldsymbol{\lambda}_J$. The constraint forces acting between the robot and the environment (e.g., the ground or ceiling) are denoted as $\boldsymbol{\lambda}_0$. If the ground-side forces become zero, the robot risks floating in mid-air. If forces such as $\boldsymbol{\lambda}_{1E}$ become zero, there is a risk of the arm disassembling or the object falling.

The target wrench (force and moment) for tracking the trajectory of the object's position and orientation can be expressed using a subset of $\boldsymbol{\lambda}_E$. The control law is defined in both feedforward and feedback forms. They are put into a soft constraint rather than a hard constraint, as suggested in [17]. To guarantee that the constraint is not violated at any of the contact surfaces, the following conditions are enforced.

$$\boldsymbol{n}_E^T \boldsymbol{\lambda}_E > c \tag{2}$$

where, $\boldsymbol{n}_E$ represents the normal vector of the contact surfaces, and c is the lower limit of the internal force pressing the surfaces against each other. Furthermore, it is crucial to simultaneously satisfy the control limit

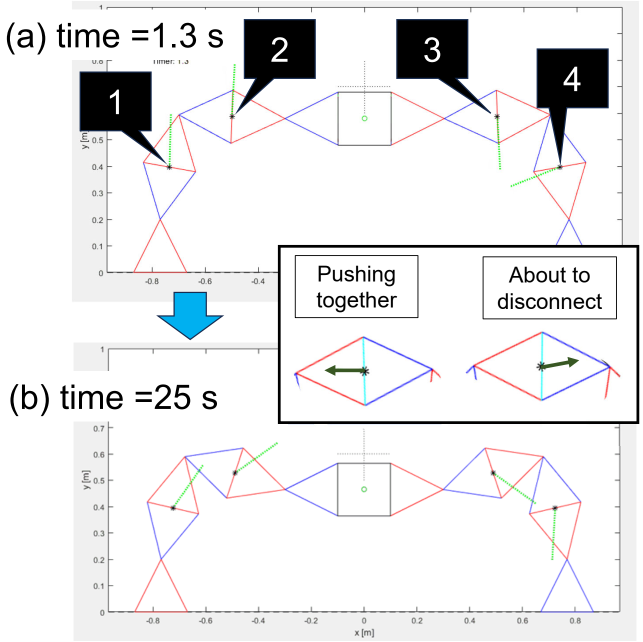

Fig. 12. Simulation of motion control by four modular robots (see supplemental video)

and range of motion, both of which are high-priority constraints.

The sequential least-squares algorithm employs (1) as the equality constraint and (2) and others as inequality constraints. It then outputs $\{\ddot{\boldsymbol{q}}, \boldsymbol{\lambda}, \boldsymbol{u}_c\}$ with the aim of minimizing the squared error of the desired wrench defined to the object. If a solution is found, it is accepted; otherwise, the structure undergoes reconfiguration, or the task itself is altered (e.g., to find an alternative route). Since a heavy-duty robot does not require high-speed motion, we are not currently focusing on optimizing over future time horizon.

A simulation result is illustrated in Fig. 12. The task is to maintain the position and orientation of the object (green triangle). Four modules stack up from the ground to cover an area centered on the target location, forming two serial manipulators. The weight of the module is 10 kg. Due to unexpected external forces (downward force of 500 N, then counter-clockwise moment of 200 Nm, both applied for 0.1 s), the position and orientation of the object are disturbed. However, it stabilizes shortly afterward, aligning with the desired posture.

Fig. 13 displays the normal contact forces on the coupling surfaces. The lower limit c in (2) is set to 100 N (the lightly shaded portion shows the inadmissible region). One can observe some cross the threshold at the moment of impulse application (10.0-10.1 s), making us to consider how much the threshold should be increased, although the dowels have pins (screws) to to prevent it from completely withdrawn.

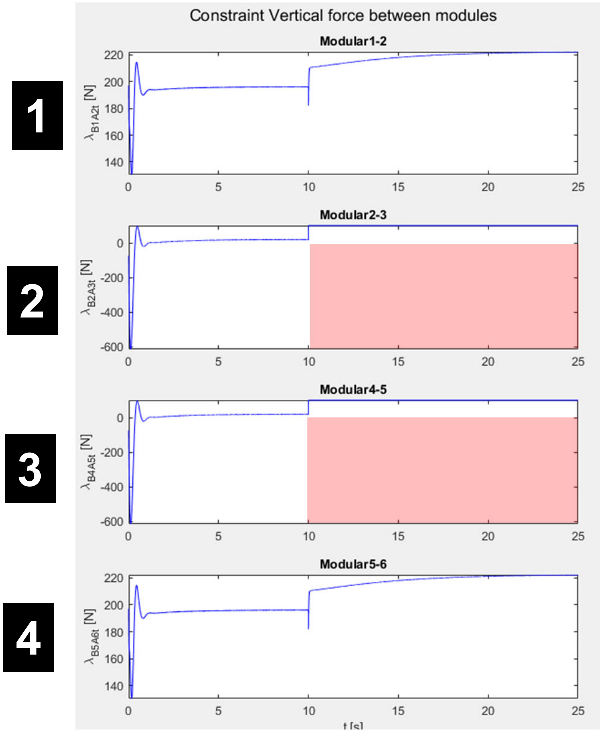

Fig. 13. Normal contact forces on connectors during the simulation.

V. Research prospects

This report presented our first challenge toward modular hydraulic robots, paving the way for reconfigurable robot concepts, proposed by many authors, to be deployed to real-world scenario. Up to now, our development is subject-wise, and not fully integrated. Nevertheless, this first report shows an important technical milestone. Our current focus is an integrated design illustrated in Fig. 14. Most of the components in this figure are already described (except for the latch mechanisms at connectors and batteries), and partially verified as shown in this report. Therefore, the next step is to make this design to real.

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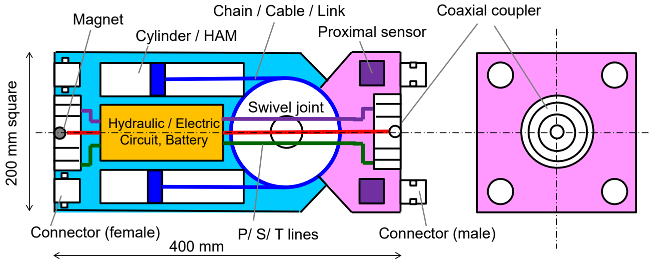

Fig. 14. Design template of Hyblock-II. The weight is 10 kg. Maximum torque is 800 Nm at 21 MPa.

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