

Modulo Cellulo: Modular Versatile Tangible Educational Robots

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Abstract—This article presents the novel modular version of the robotic platform Cellulo, a versatile handheld robot initially designed as an educational robot. The use of Cellulo in different contexts and applications over the years has highlighted the need for modularity. Modularity adds versatility by increasing the spectrum of functionalities of the robot, as well as more robustness. Modulo Cellulo consists of three modules: a main module, a battery module, and an interaction module. We describe the new Modulo Cellulo platform, the different modules design, the mechanical and electrical interconnectivity between them, the new adaptive controller, and the application development framework. As a show case, we present the addition of the reconfigurable robot Mori as a module for Cellulo, in an activity envisioning the collaboration between reconfigurable swarm robots.

I. INTRODUCTION

The Logo Turtle created by Papert [1] in the 1980’s can arguably be considered the first educational robot ever and the father of the Robots for Learning (R4L) domain. Its goal was to provide learners a “computational object to think with”, in line with Piaget’s constructivist theory that learners should be proactive builders of their own knowledge rather than passive recipients of inert and absolute information provided by outside sources [1]. The Logo Turtle was closely linked to the then-emerging “computer culture”, resulting in the concept of “allowing learners to program a simple robot”, which spawned the programmable learning robot movement.

Stemming from these origins, two main directions have emerged in the area of R4L. The first movement considers robots as tools [2]. These robotic platforms are mostly custom designed to teach programming and other closely related Science, Technology, Engineering and Mathematics (STEM) concepts. The second direction is rather young and emerged with the advances in the human-robot interaction (HRI) field [3], where robots would rather play the role of socially capable peers or tutors.

Robots at the intersection between tools and socially-capable agents, such as Cellulo [4], specifically open novel avenues for their use in educational context. The Cellulo robots act as agents representing abstract as well as concrete objects. With this representation, several properties can be

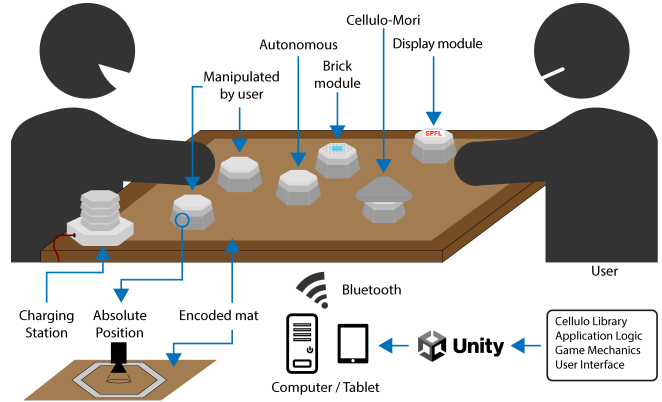


Fig. 1: The Cellulo platform

delivered to the learner, through kinematic motions, such as velocities and accelerations, and behaviours in collective groups. Through their tangible presence, the robots are directly used to make tangible what is currently intangible in learning, by enabling closer handheld and haptic interaction with the learning activity.

Since its creation, Cellulo robots were used in multiple studies, including, among many others, handwriting [5] (where Cellulo’s motion was used to make the ductus of letters visible), mathematical concepts like functions [6] (where Cellulo’s force haptic feedback was used to convey the relation between x and y in a linear function), chemistry such as particles in matter (where the collective of many robots was used to convey atoms behaviours from one state to the other).

Cellulo was designed following five key design principles: 1) Ubiquity: with the analogy of a “pen and paper”, this principle refers to blending our robotic platform into the daily learning routines of classrooms. 2) Practicality: the robot can be used in a classroom setting within real lessons, therefore our platform must be flexible yet reliable to allow continuous usage in such settings. 3) Versatility: rather than a tool that is only useful for teaching a single topic, a learning platform should be used in a variety of learning settings and disciplines. 4) Tangibility: inspired by Papert’s constructionist principles, the platform should inspire hands-on learning. 5) Multiplicity: the possibility to have multiple robots as well as multiple learners within the same activity, the robots should enable social interaction and collaboration within the learners.

We introduce Modulo Cellulo, an upgrade and a successor of the existing Cellulo which provides modularity to the

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core structure. This modularity reinforces the practicality principle, by making the robot more robust to failure as it is easy and practical to change the parts. It reinforces the ubiquity and versatility principles, by introducing task-specific functionalities which can be put together by assembling the needed modules. It supports the tangibility principle as it enlarges the spectrum of tangible interaction possibilities. Modularity strengthens the social collaboration between learners who might have robot with different but complementary functionalities. Introducing modularity induced mechanical, electrical, and software changes and enhancements. After reviewing the relevant literature, the design and capabilities of Modulo Cellulo is presented in Section 3 and 4. Section 5 showcases a reconfigurable swarm robot, made possible by the new design. Finally, we provide a summary and discuss future work in Section 6.

II. RELATED WORK

Modulo Cellulo is inspired, and in turn contributes to, a number of fields: Tangible User Interfaces (TUIs), Educational Robotics, and within that, modular robotics.

A. TUIs

Tangible User Interfaces, including actuated and shape changing interfaces, have been one of the main streams in the field of HCI, investigating the function of dynamic actuation capabilities for interaction design. HERMITS [7] augments small self-propelled robot with passive components designed as customizable mechanical add-ons. Linking TUIs with Virtual reality helps rendering haptics for VR objects as in HapticBots [8]. Lastly, RoboGraphics [9] introduced an application for a dynamic tactile graphics helping visually impaired participants explore data quickly.

B. Educational robotics

Educational robotics is currently split into two main research areas. One focuses on social, typically humanoid, robots and the potential of impactful human-robot interaction in learning context [3]. The other focuses on the use of robots in STEM subjects. Robots developed and used to this purpose are programmable mobile robots such as Thymio¹ which is being widely used in primary and secondary schools to teach programming. Aside from the field of “using robots to teach robotics”, [2] reviews the existing platforms and toolkits used in learning activities related to mathematics and physics.

Modular robotics: Alongside pre-assembled robots, modular robotics kit have gained popularity, aiming at motivating students to build, design and create. Modular robotics kit usually consist of a collection of robotics units or modules that can be attached and detached to yield a variety of combinations. Examples of such systems are the famous LEGO Mindstorms, Fable II [10], or Cubelets [11]. Modularity reinforces the versatility principle by increasing the possible set of usages.

Modulo Cellulo explores the design and use of robots in education where it is not to be regarded as a robot (i.e. not

programmed or assembled) nor as a social tutor; but rather as an “on-demand” assistance tool for teachers, that may be utilized in a variety of disciplines.

III. PLATFORM DESIGN

Fig. 1 illustrates an overview of the Modulo Cellulo platform, which consists of three main components:

- 1) The *workspace*, consisting of printed sheets of paper “augmented” with a dot pattern [12]. Depending on the activity requirements, the graphics on the paper can be designed or changed accordingly.
- 2) The *Modulo Cellulo robots* themselves, which are modular tangible haptic-enabled mobile robots. They can be either manipulated by a user or move autonomously, and provide versatile user interaction experiences.
- 3) A central *orchestrator* (usually a laptop or tablet) which connects to the robots through a star network composed of point-to-point Bluetooth SPP links.

Software Design & Orchestration

Following the principles discussed in the Introduction, we design the software architecture to be activity-driven rather than driven by the platform’s capacities. Concretely, the robot firmware only implements on-board essential software components which are latency or bandwidth-sensitive, such as the image processing for localization, the motion controller, the haptics controllers, the battery management system, the grasp detection, and the user interaction engine. Each robot is connected through a Bluetooth Serial Port Profile (SPP) channel to a main orchestrator that runs a UNITY² application corresponding to the activity. As part of the Modulo Cellulo platform design, we decided to use Unity since it provides, from a software development perspective, a powerful environment for the fast development of rich activities, thanks to its game engine and built-in functionalities. In addition, from a deployment perspective, thanks to its portability to many platforms and devices, Unity allows to deploy applications on desktop computers running Linux, Windows, or Mac operating systems as well as consumer mobile devices or tablets, or even VR headsets (as demonstrated in [13]). To take advantage of the cross-platform deployment of Unity, we developed a cross-platform Unity plugin³ which enables a seamless connection to the Cellulo robots through Bluetooth, allowing to have the Cellulo robot as a hardware-in-the-loop in any designed activity. Although our platform is centralized by design, lacking robot-to-robot direct communication due to the star topology of our communication network, robot-to-robot interactions can always be simulated through the Unity game engine by using built-in sensors.

IV. MODULAR ROBOT DESIGN

A. Overview

Modulo Cellulo robots are conceptualized to be composed of three modules: A main module which contains essential

¹www.thymio.org

²<https://unity.com/>

³available at <https://github.com/chili-epfl/cellulo-unity-plugins.git>



Fig. 2: Main Module (bottom) and battery module (top) connected via sliding rails, magnets and pogo pins

functionalities, a battery module containing the power management system, and a user interaction module which can be changed and adapted based on the activity requirements.

B. Connection between modules

From a mechanical perspective, the connection between modules need to be robust enough to not break down during use, but at the same time easy to assemble and disassemble. The connection interface between modules is designed to be intuitive for most users. The sliding rails (Fig. 2) provide a solid connection between modules and ensure the user correctly aligns the modules one another. Magnets provide an extra force to align the modules and avoids unintentional sliding. As for the electronic connections, spring-loaded pogo pins touch target contacts and form a stable connection. The combination of sliding rails and pogo pins (Fig. 2) can thus eliminate the shortcomings of the commonly seen header pins and sockets connections (such as stacking Arduino shields). A pair of pogo pins in the middle of the connection port is the power supply for all modules, providing direct battery access. Two pairs of pogo pins on the connection port ensure data transmission with the UART and I²C protocols. The two pins separate from the connection port are used for charging and only exist on the battery module (Fig. 2).

C. Main Module

The main module is designed to be the *base* of the whole system. The main module controls the movement of the robot, while the other modules act as *worker* devices managed by the main module. The main module shown in Fig. 3 includes the main micro-controller (chosen to be a PIC32) and is responsible of all the main computational work. This includes five essential tasks: localization, locomotion, wireless communication, coordination between modules, and grasp detection.

1) *Localization*: We use the same fast and accurate localization system originally developed for Cellulo, which is based on a dense, deterministic and well-defined optical microdot pattern printable on regular office printers. More details can be found in [12]. The main module is equipped with a global shutter image sensor facing downward which

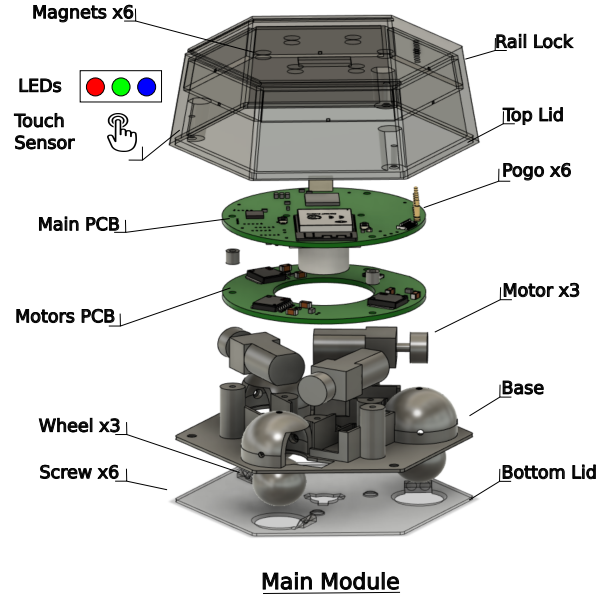


Fig. 3: Exploded view of the Modulo Cellulo main module

acquires an $\sim 1\text{cm}^2$ region of the printed sheet at about 93 Hz, from which a 3 DOF pose (x, y, θ) can be extracted. This approach provides a global and absolute localization with $\sim 0.17\text{mm}$ and $\sim 1.5^\circ$ accuracy without the need for any calibration. Furthermore, thanks to the hardware design and the placement of the camera beneath the robots, we can provide perfect robustness against external illumination conditions, as well as instant recovery from kidnapping, thus allowing any manipulation to be performed without any adverse to localization performance.

2) *Locomotion*: Although locomotion doesn't have its own module mechanically, the modularity principle is followed with the electronics design, as we dedicate a separate PCB for the motor drivers for two main reasons: 1) to have a better heat distribution for the drivers and 2) to leave room for changes in the locomotion system (to enable a faster or more powerful drive, for example, or even passive, non-actuated, modules). The current locomotion drive is the permanent-magnet assisted omnidirectional ball drive, detailed in [14] and shown in Fig. 3. In addition to providing holonomic motion and mechanical robustness against intensive user manipulation, it enables kinesthetic haptic feedback in the form of force/torque output on the learner's hand, as well as backdrivability assistance to overcome the natural impedance of the robot due to the friction of the wheels on the paper when the robot is moved by the user.

Adaptive Motion Controller: Introducing modularity to the Cellulo robot implies the possibility of dynamic changes to the physical properties of the robot, requiring an adaptive motion controller. A non-adaptive system, would either be unable to overcome friction with a heavy module or overshoot any speed constraints with a lighter load. Moreover, in the case the user interaction module is a self-reconfigurable

modular robot (see Sec. V), the module's weight and centre of mass can dynamically change in real time. We thus implemented an adaptive controller for the Modulo Cellulo, able of self-tuning its control parameters over time. The motion control of Cellulo was an open-loop velocity controller which incorporates wheel orientation, weight, and friction for non-holonomic motion [14]. The new controller is composed of two parts: A feedback linearisation component to decouple and linearise the system, and a Model Reference Adaptive Controller (MRAC) that adjusts the parameter gains given the online controller performance [15]. Through the feedback linearisation module, the augmented system to control becomes a triplet of decoupled, perturbed, simple integrators:

$$\dot{q} = b_q \cdot (v_q - f_q(X)), \quad q \in \{x, y, \theta\} \quad (1)$$

where $f_q(X)$ is a term encompassing all perturbations on the system, including friction and manual user input. b_q is a value that depends on the system modelling ; unknown but constant while the mass of the system is unchanged. v_q is the control input that contains the controller parameters.

The control input is composed of a feedback term, a feedforward term, and a perturbation compensation term:

$$v_q = -\hat{k}_{pq} \cdot \dot{q} + \hat{k}_{rq} \cdot r_q + \hat{\theta}_q^T \cdot \Phi_q(X) \quad (2)$$

where $\Phi_q(X)$ is a vector containing all the linearly separable components of $f_q(X)$ that can be measured. Most importantly, it can be extended to suit the perturbation model of specific tasks. The parameters \hat{k}_{pq} , \hat{k}_{rq} , and $\hat{\theta}_q$ are updated based on the error e_q between the system response and the reference model response:

$$\begin{aligned} \dot{\hat{k}}_{pq} &= \text{sign}(b_q) \cdot e_q \cdot \gamma_{pq} \cdot \dot{q} \\ \dot{\hat{k}}_{rq} &= -\text{sign}(b_q) \cdot e_q \cdot \gamma_{rq} \cdot r \\ \dot{\hat{\theta}}_q &= -\text{sign}(b_q) \cdot e_q \cdot \Gamma_{\theta q} \cdot \Phi(X) \end{aligned} \quad (3)$$

where γ_{pq} , γ_{rq} , and $\Gamma_{\theta q}$ are the learning rates.

To assess the performance of the proposed adaptive controller, we compared it against the open-loop controller, on two Cellulo robots. The two robots were tasked to make back and forth motions at increasing speeds (from 50 mm/s to 150 mm/s with intervals of 25 mm/s) under 5 different added weight configurations. Each configuration was repeated 3 times, varying the initial pose. Results are shown in table I. The difference is significant (p-value < 0.05) for any added weight, with the maximum improvement registered with an added weight of 200 g (100% with respect to the weight of the robot), for an average 19% performance increase using the adaptive controller.

3) *Wireless Communication*: Each robot communicates with the controller wirelessly. To do that, the main board is equipped with an ESP32 which is acting as a bluetooth bridge. Moreover, the ESP32 can be programmed over-the-air making it easier from a deployment perspective to add new features and functionalities, including peer-to-peer communication for which work is ongoing. The wireless

TABLE I: RMSE percentage comparison between open-loop and adaptive controllers. p-values are given by the Mann-Whitney U test. Effect size is the Common Language Effect Sizes, i.e. the percentage of open loop runs where the error was higher than for the adaptive one.

Added weight[g]	Mean RMSE open-loop[%]	Mean RMSE adaptive[%]	p-value	Effect size
0	58.68	61.27	0.33	0.42
50	68.07	58.48	0.001	0.74
100	71.45	63.67	0.009	0.70
150	77.18	61.00	3.6e-8	0.91
200	83.30	64.38	5e-7	0.85

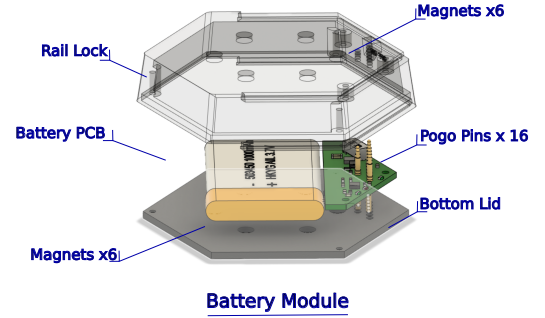


Fig. 4: Exploded view of the Modulo Cellulo battery module

communication takes care of sharing information categorized in two main lines: 1) Transmitting local robot information such as robot pose, battery status, user interaction data, and debug data if requested, such as image frames, or on board profiling; 2) Receiving commands such as setting goal velocities, tracking goal poses, haptic command, power commands (reset, sleep) and commands for the user interaction module.

4) *Coordination between modules*: The main module is also responsible for managing and detecting which module is connected to it. The main firmware has two ways to detect the attached module: by a wireless command through the app, or by an automatic scanning of devices in the I²C line.

5) *Grasp Detection*: To detect if the module is being moved by the user or not, conductive thin films are placed inside the sides of the main module, to act as capacitive touch sensors. This is a direct consequence of the feedback from the use of Cellulo, where the placement of the touch sensors at top was not reliable enough where users usually hold the robots from the sides in order not to cover its illuminated top.

D. Battery module

The battery module (Fig. 4) is designed to be a separate unit in order to increase the practicality of the robot's usage. If the battery is drained, the user shall not wait for a full recharge to continue their activity, but rather just swap the battery module with a fully charged one. This module includes a rechargeable battery and a Battery Management System (BMS). A Lithium polymer battery (LiPo) is embedded in the battery module on account of higher energy per unit

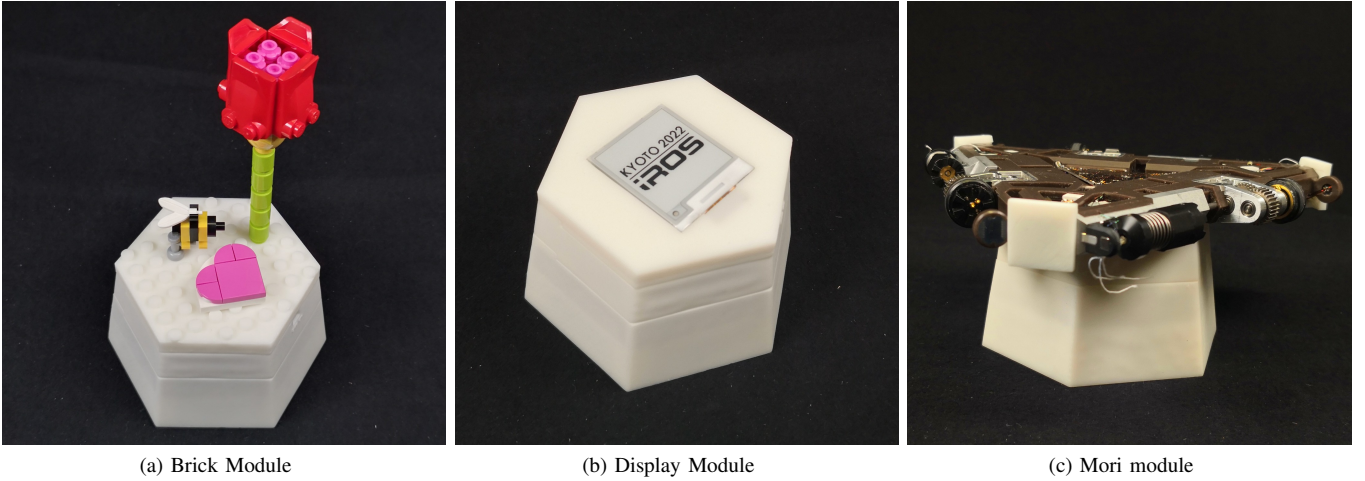


Fig. 5: Examples of different type of user interaction modules

volume and reliable battery safety. The BMS is composed of a BQ27441-G1 System-Side Impedance Track™ Fuel Gauge and a BQ24075 Standalone 1-Cell 1.5-A Linear Battery Charger with PowerPath. The BQ27441 provides battery information such as remaining battery capacity (mAh), state-of-charge (%), and battery voltage (mV). The BQ27441 uses I²C serial bus for communication with the main module. The BQ24075 integrates Li-Ion linear chargers and system power path management. The LiPo battery is with 1200mAh capacity: A constantly autonomously moving Cellulo, would last around 1 hour. A charging station is designed to stack the battery modules above each others as illustrated in Fig. 1.

E. User Interaction Module

The user interaction module is the top module of Modulo Cellulo and provides the most versatile options. The basic UI module is equipped with 6 RGB-illuminated capacitive touch buttons allowing simple touch interaction and visual feedback through the LEDs. We can think hereafter of a multitude of different options for a user interface. Examples include a display module (Fig. 5b) which reveals richer information, and can be used in the activity to disclose hidden information embedded in the map as in [16]. Another option is a passive attachment with the footprint of LEGO® bricks Fig. 5a allowing the addition of passive props and personalized designs on top of Modulo Cellulo. Another passive attachment, motivated by the use of Cellulo in an upper limb rehabilitation scenarios [17], is constituted by a grasping aid helping people with mobility impairments grasp and hold the robot. Other UI modules currently under consideration are tactile displays with thermal, or shape changing. A thermal display could be a Peltier element thermoelectric cooler (TEC) which can generate hot and cold feeling in an application around heat transfer for example. The shape-changing display can act like Braille to help the visually impaired people. Apart from tactile, a sonic module including a mic and a speaker can add a whole new dimension of spatial and social interaction.

Until this point, the robots were used to be the representation of point-like objects, independent and detached one from the other. However, adding a reconfigurable top module to Modulo Cellulo paves the way for the representation of objects (or concepts) via shapes collectively generated by multiple robots linked together.

V. SHOW CASE: MODULO CELLULO-MORI

We demonstrate the benefits of Modulo Cellulo’s modularity by incorporating the Mori modular robot on top. The Mori is a self-reconfigurable modular robot and consists of quasi-2D triangular modules which are able to connect to other modules with the same connector and rotate around the control joint [18]. These modules provide a high ratio of area to volume, allowing the Mori to fold into large 3D shapes and structures with relatively little mass. By integrating Mori on top of Modulo Cellulo, we incorporate the strengths of both robots. The Mori provides Modulo Cellulo with the ability to move out of plane, as well as link to other robots into large structures. Modulo Cellulo ensures faster planar motion and localization, along robustness to human manipulation.

The user interaction module which enables linking Modulo Cellulo and Mori is aptly named a “Cellulo-Mori”. The module consists of a mechanical anchor and electronics to integrate a Mori onto Modulo Cellulo. The anchor spans the width of the Mori and latches onto mechanical holding points on the Mori’s corners. The electronics provide power from Modulo Cellulo to the Mori and link to the Modulo Cellulo’s controller, including wireless functions. Thus, the Cellulo-Mori can be operated via the same wireless protocol as Modulo Cellulo, easing simulation-to-real transitions. The Cellulo-Mori can transfer Mori modules between each other, including across multi-level planes as otherwise impossible. Linking Mori together can lift Cellulo off the ground, over gaps and to different elevations. Activities can explore collaborations where two users have to work together, with one user controlling Cellulo and the other Mori. This show case demonstrates the adaptivity of the Modulo-Cellulo. The

user interaction module not only provides the ability to augment user interaction, but can incorporate other robots which introduce different elements to the activity design. We observe that integrating two versatile robots allows for each to benefit from the strengths of the other to create new physical operations. Modularity eases the integration of external devices onto Cellulo, providing new methods to explore a large spectrum of learning activities and disciplines.

Future work will introduce user activities studying the emergent behaviour of multi-robot systems and people's understanding of said behaviour (Fig. 6). A flock of birds or the self-organization of social insects are examples of natural emergent behaviours where macro patterns arise from the interaction of micro agents. Not only is this an important domain to learn about on its own, but it actually consists of a "powerful idea" [1] that cuts across disciplines and can lead to the understanding of a large class of physical and social phenomena taught as conceptually different subjects. We envision the Modulo Cellulo platform to be a promising learning environment, building on the finding that whenever students have the opportunity to take the point of view of an atom, a fish, or an ant, they are more ready to conceive complex systems [19].

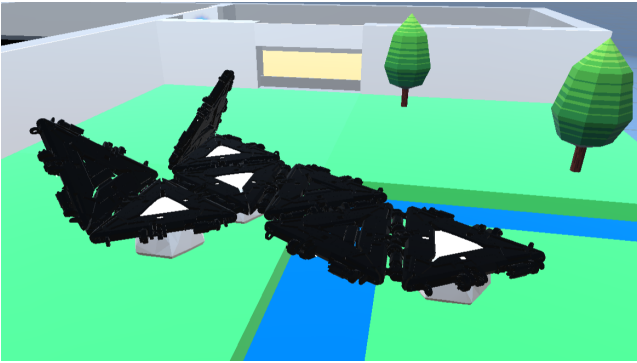


Fig. 6: Modulo Cellulo-Mori - Example of a collaborative game to go over obstacles, inspired by the army ant behavior of building bridges

VI. CONCLUSION

In the paper, we present a novel modular versatile tangible robot, the Modulo Cellulo. We detail its design and implementation from the different facets of mechanical, electrical, control and software design. The resulting platform is: 1) ubiquitous by being able to easily blend in the classroom setup; 2) practical, by consisting of modular robust wireless robots operating on a paper workspace with a straightforward setup, not limited to a specific deployment method thanks to the Modulo Cellulo cross-platform activity design environment in Unity; 3) versatile, by enriching and blending in (rather than changing) the current teaching practices of various disciplines thanks to different interaction modules; 4) tangible, by being able to move the robot and receive haptic feedback; 5) while asocial from a robot perspective, enabling social interactions through the possibility of having

multiple robots and multiple users interacting simultaneously. As a show case, we also present Cellulo-Mori, the integration of Modulo Cellulo with the Mori robot, resulting in a reconfigurable swarm of robots. For future work, we are continuing to design new interaction modules. Moreover, we are designing learning activities involving Modulo Cellulo and Cellulo-Mori, to highlight the potential and effectiveness of such a powerful platform.

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