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The Deformatron Robot: a Biologically Inspired Homogeneous Modular Robot

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***Abstract*— The Deformatron robot is a homogeneous, modular robot. The Deformatron modules can play one of three roles in the physical structure of the robot: bone, tendon, and muscle. These roles are inspired by their biological counterparts. This combination of roles gives us a modular robot which potentially may have enough structural strength and actuation power to manipulate its environment and work in three dimension even in the presence of gravity. In this paper we present our preliminary LEGO-based prototype of the Deformatron robot. We measure and analyse the properties of the system in terms of structural strength and actuation power. Finally, we conclude that the Deformatron concept may provide an avenue of research which may make modular robots stronger and better suited for real world task environments.**

***Index Terms*— Modular robotics, embodied artificial intelligence**

I. INTRODUCTION

One of the challenges in modular robots is to build systems with enough actuation power to manipulate the robot's environment. In general, modular robots can manipulate the environment either through a shared surface or a shared point. In surface-based manipulation many modules touch the object to be manipulated and combine their actuation power e.g. many modules can stay under a table and combine their actuation power to lift the table. The other alternative is point-based manipulation. In point-based manipulation only a limited number of modules touches the object and thus cannot take advantage of parallel actuation to a high degree. Therefore, the actuation power has to be transferred from inside the robot to these modules. In real application, it is often difficult to apply surface-based manipulation because of space constraints and therefore point-based manipulation is crucial for robots acting in the real world. This paper takes a step towards addressing the problem of how to obtain point-based manipulation in a modular robotic system.

Point-based manipulation is done every day by a wide range of animals and therefore it seems natural to be inspired by their design. In the biological world, the key elements are bones, tendons, and muscles. Merriam-Webster On-Line dictionary define a tendon as: " tough cord ... that unites a muscle with some other part (as a bone) and transmits the force which the muscle exerts". That is, in the biological world, tendons transmit muscle power to bones. This is the concept we are trying to transfer to modular robots.

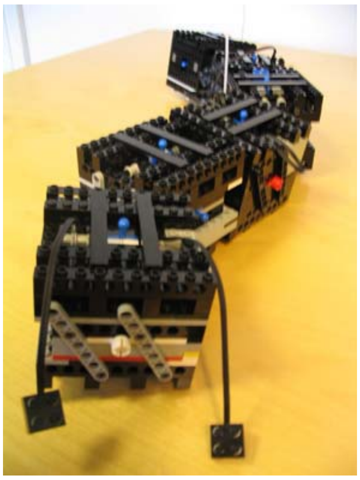

Fig. 1. This figure shows the Deformatron modules in a chain configuration. Every second module in the chain form rigid, strong connections and the modules in between form flexible connections which can be actuated.

The goal of our work is to understand how to develop atoms or modules from which a wide range of tendon, muscle, and bone-based robots can be built, as opposed to building a specific robot as explored by many researchers see for instance [1].

In this paper we present the Deformatron robot (see Figure 1). The Deformatron robot is a homogeneous modular robot. The modules are built from LEGO and are 8cm cubes with a connector placed in the centre of each face. There are three female and three male connectors based on ball and socket connection. One of the male connectors can be actuated and can be extended up to 4cm. This arrangement of connectors makes it possible to connect modules in many different ways, allowing you to build a wide range of robot bodies.

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In experiments, we demonstrate how the Deformatron modules can be combined to create a muscle-like structure and measure how the strength of the muscle scales with the number of modules. We also demonstrate how modules can be connected to form a joint. Finally, we demonstrate how a rigid bone can be constructed.

We conclude that using the Deformatron concept we can build these functional units and that these units may form the basis for point-based manipulation and thus enable us to build stronger modular robots. However, the current prototype of the Deformatron modules is preliminary and needs further development before the goal can be realized in practice.

II. RELATED WORK

Modular robots can be divided into two classes. Systems where modules are rigidly connected or systems where modules are flexibly connected. The I-Blocks system [7] represent an example of a rigidly connected system. The basis of this system is LEGO DUPLO bricks with embedded electronics, sensors and actuators. The connector is the LEGO connector and thus the connection is rigid. At the other extreme is the AMOEBA robot [11]. In this system modules are connected with shape memory alloy (SMA) providing a flexible bond giving the robot an Amoeba-like functionality. The SMA contracts once heated, but the connection still does not provide structural strength. The Deformatron modules combine the functionalities of these two extremes in one modular system in the sense that each module can form both rigid and flexible actuated connections.

A few multi-robot systems also allow individual robots to connect to each other. These systems include the SWARM-BOTS [8] and the Millibot train [2]. The SWARM-BOTS can, using two different connector systems, form both rigid and flexible connections to another nearby robot. In this sense the functionality is similar to the Deformatron robot. However, the rigid connector is only able to lift one robot and the robot does not provide structural strength to allow stacking of robots. This is also true for the Millibots system. The CEBOT system also has rigid connectors, but they are not used for lifting [4]. Another related system is proposed by Ishiguro et al [5]. In this system modules are circular two-dimensional and can make flexible connections with neighbour modules, but again the modules of this system do not provide structural strength.

Self-reconfigurable robots are a kind of modular robots where modules dynamically can connect to and disconnect from each other and thus the shape and connection topology of these robots can change over time. Self-reconfigurable robots can be divided into three classes: chain, lattice, and hybrid. In chain-type self-reconfigurable robots, modules are often connected in tree structures where the branches consist of chains of modules playing the role of limbs. Examples include the PolyBot [12] and the CONRO system [3]. These robots are characterized by providing a platform on which it is relatively easy to implement locomotion gaits and even let the locomotion gait depend on the environment. However, chain-type self-reconfigurable robots also have limited passive structural strength. In order to overcome this problem and other problems lattice-based systems are being investigated, e.g. the Crystalline robot [10]. In these systems, modules are organized in a lattice from which the robots gain structural strength. Unfortunately, this constrains the interaction with the environment because movement outside the predefined lattice structure is only possible on the surface of the robot. The features of these two systems have been combined in hybrid systems, these systems can exist in both chain and lattice form, but not at the same time. Examples include ATRON [6] and M-TRAN [9]. Typically, they maintain a chain-type configuration for locomotion and a lattice-type configuration when reconfiguring. In this work, we develop a modular equivalent in the sense that modules can both exist in a rigid lattice structure and in flexible chain structures. The idea is to give up self-reconfiguration capabilities for a simpler design.

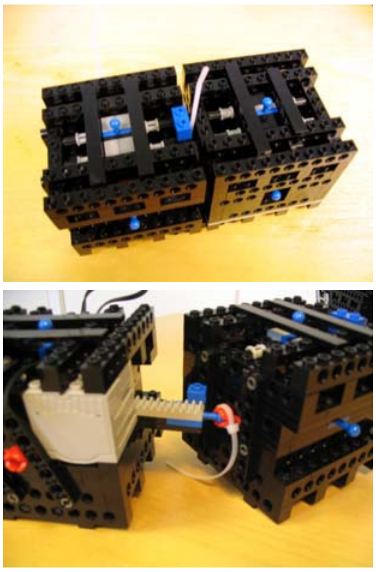

Fig. 2. Most connections in the Deformatron system are rigid and strong as shown in the top photo. However, one of the male connectors can be used to make flexible connections as shown in the bottom photo.

III. THE DEFORMATRON MODULE

The current prototype of the Deformatron robot consists of six modules. The modules are three-dimensional and built from LEGO. The modules are cubic with a side length of 8cm and weigh 190g. They have six connectors located in the centre of each face. There are three female and three

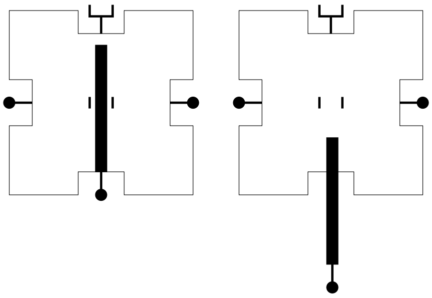

Fig. 3. Schematics of the Deformatron module. One of the male connectors can be actuated as shown.

male connectors using ball and socket-type joints to connect. One of the male connectors can be extended by 4cm and is equipped with sensors which can detect when it is fully extended or contracted. We refer to a module connected to a neighbour using the extendible male connector unactuated as a tendon module, a module connected to a neighbour using the extendible connector actuated as a muscle module, and a module who not using the extendible connector as a bone module. The schematic of the Deformatron module is shown in Figure 3. The current prototype is a mechanical prototype and as such does not have on-board batteries and processing power, but is controlled using an external LEGO MINDSTORMS RCX.

IV. EXPERIMENTS

We have done three different experiments with the Deformatron modules. In the first experiment, we demonstrate how modules can be combined to produce muscle like structures with actuation power proportional to the number of parallel module chains in the muscle. In the second, we demonstrate how to make an actuated joint that can transfer the translatory movement of muscles to a rotational movement. Finally, in the third experiment, we show how bone structures can be built to transfer movement over longer distances. Overall, these building blocks combined may provide the basic functionality needed to enable the system to do point-based manipulation.

V. MUSCLE

The muscle modules can essentially be thought of as the robotic equivalent to biological muscle fibers. The actuation range R can be calculated based on the size s of the individual muscle module, the actuation range of the individual module r, and the number of modules in the longest chain of muscle modules N_{chain} in the muscle:

$$R = [\,N_{chain}\; s; N_{chain}\; (s + r)]$$

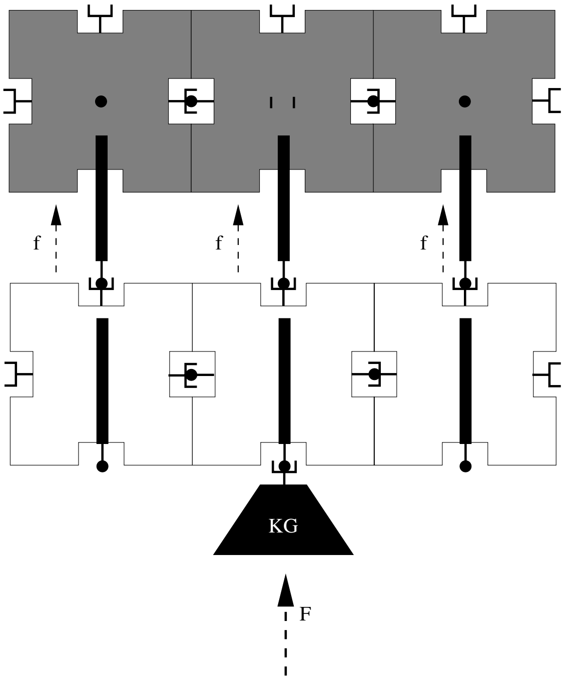

Fig. 4. This figure shows the schematics of a muscle made from six modules. The dark gray boxes are muscle modules and apply forces to the three white bone modules below. These bone modules transfer the actuation power to the object the muscle has to lift.

The actuation force of a muscle can be calculated based on the force of individual modules f_{module} and the number of modules in a cross section N_{cross} of the muscle perpendicular to the direction of the force.

$$F = N_{cross}\, f_{module}$$

You can also design muscles with different force to length profiles by having different number of modules in different cross sections.

Using our Deformatron modules, we have built two different muscles. The first muscle is the simplest muscle possible, built from one muscle module. The second is built from three muscle modules parallelly connected to three bone modules, as shown in Figure 4. The bone modules transfer the muscle-generated force to the point used for manipulation. We have measured the maximum force these muscles can generate. One module generates a contraction force of $5.9N \pm 0.3N$ and has an activation range of $[8cm; 12cm]$. The three modules generate $14.2N \pm 0.8N$ and have an activation range of $[8cm; 12cm]$. This result shows, as expected, that the forces of three muscle modules add up, but also indicates that some of the force is lost due to friction.

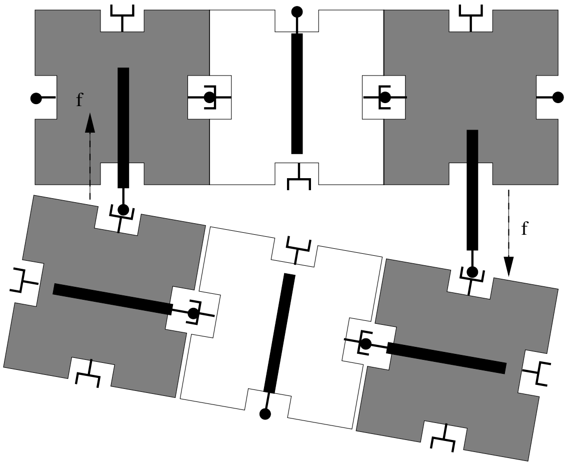

Fig. 5. This figure shows the schematics of a joint made from six modules. The top left muscle module is contracted and the top right muscle module is expanded resulting in rotation of the joint. The bottom-left and right muscle modules are needed to satisfy the geometric constraints.

The force of the muscle is $14.2N$ which is enough to lift nine modules. This is a relatively limited force for a muscle consisting of six modules (three muscle and three bone modules). However, it can be improved by changing the gearing of the individual modules to find another trade-off between speed and force.

VI. JOINT

In biological systems the translatory movement of a muscle is converted into a rotational movement by a joint. The physical design of our modules prevents us from copying this mechanism directly, but instead we can get a joint-like functionality from modules arranged as shown in Figure 5. Here the rotational movement is generated by having two muscle modules on each side of the joint contract and expand, respectively. The joint can be made more powerful by using tendon modules to transfer actuation force from larger muscles further away. The joint can also have a wider rotation angle by adding another joint segment.

VII. BONE

It is trivial to construct a bone, because you just connect bone modules to form a bone of the desired shape (see Figure 6 for an example). However, in order for this to work the connection between the modules has to be strong and rigid.

The rigidity is handled by designing the module so that they have a large contact surface when connected. This prevents any pitch and yaw between modules. However, a large contact surface alone does not prevent roll. Roll can be eliminated by embedding pegs in the male faces and matching holes in female faces, however, this has not been implemented in our current prototype.

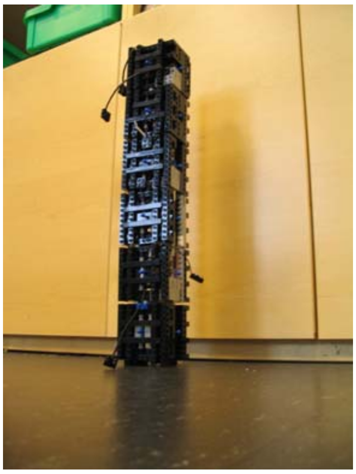

Fig. 6. This figure shows six modules connected to form a module bone that can be used to give the modular robot structural strength. Note that this is possible because of the large contact surface and fairly strong connections between neighbouring modules.

Fig. 7. This picture shows a close-up of the reinforced ball and socket joint which connects modules.

The other important property of the connection is its strength. In the current prototype we use a reinforced version of the ball and socket joint provided by the LEGO kit shown in Figure 7. This connection gives a connection force of $14.6N \pm 0.4N$. This is not satisfying and in the next generation of the prototype we will use hooks to make stronger connections.

VIII. DISCUSSION

We have now seen how the Deformatron prototype can be used to make three different functional units: bone, muscle, and joint. However, this alone does not provide a solution to point-based manipulation. In order to reach this goal these functional units have to be combined into a robot capable of point-based manipulation. This is more than we can do with our current number of modules, but our future work involves construction of more modules which may enable us to demonstrate point-based manipulation. Eventually, miniaturization is needed to create a truly useful system.

The Deformatron prototype is only a mechanical prototype and as such does not contain power sources, processing power, and means for inter-module communication. We can add this to the prototype by using electronic designs from existing systems. We can choose to implement a fully distributed system where each module is self-sufficient and autonomous as it is often the case for modules for self-reconfigurable robots [6], [9] and at the other extreme we can choose to use a centralized design. However, since our modules are not mechanically autonomous, it may make sense to use a less than a fully distributed system. On the other hand, making a centralized system may introduce communication bottlenecks in the system and may make the system vulnerable. In practice, a hybrid will probably be the most appropriate. This also points towards a heterogeneous alternative to our homogeneous approach.

The Deformatron system can be simulated using a hybrid self-reconfigurable robot. The self-reconfigurable robot then needs to be in lattice structure when providing structural strength and a group of modules can provide muscle functionality. Doing this represents an interesting line of research.

It is obvious that our implementation represents a preliminary prototype. However, we still think that we, at this early stage, can point out some of the potential advantages of the Deformatron concept:

- **Robust**: The robot is robust to module failure, because its functionality is a result of many modules working together and does not depend on correct functionality of each module. E.g. a muscle made from many modules does not stop working just because a few modules fail.
- **Versatile**: The ability to form both rigid (bone) and flexible (muscle and tendon) substructures makes the concept highly versatile.
- **Cheap**: The robot is built from homogeneous modules that can be mass produced and therefore the robot is cheap compared to complexity.
- **Force addition**: Modules can be added to the system to form a more capable robot. The forces of the modules can be made to add up and therefore the strength of the robot can increase with the number of modules.
- **Scalable in size**: The modules can be miniaturized leaving the performance of the robot at macro scale unchanged. E.g. a muscle made from miniaturized modules will perform in the same way as a muscle made from macroscopic modules as long as the actuation range and force vs. length profile is the same.

The future plan is to develop the prototype further starting with the connector and then building more modules. In the long term we hope to verify the potential advantages listed above.

IX. CONCLUSION

In this paper we have presented a novel modular robot called Deformatron. The Deformatron robot is built from homogeneous modules which can play three different, biologically-inspired roles in the physical structure of the robot: muscle, tendon, and bone. The goal is to build a robot from these Deformatron modules which can achieve point-based manipulation.

We have taken the first steps towards this by demonstrating how basic functional units such as muscles, joints, and bones can be built from a LEGO prototype of the Deformatron module. However, before these functional units can be combined into a robot able to do point-based manipulation, we need to make more modules and stronger connectors.

Overall, the Deformatron concept provides a new avenue of research which may make modular robots stronger and better suited to handle real-world challenges.

X. ACKNOWLEDGMENTS

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