C-Balls: A Modular Soft Robot Connected and Driven via Magnet Forc.
are modules based on pressure-operated actuation, which are safety and adaptability to robotic systems [12]. Soft pneumatic actuator composed of two elastomeric strands, which provide interdependent axial and radial expansion [16]. A few of researchers have studied on controlling method for soft modular robots. Large and continuum deformation modular robot is controlled by autonomous decentralized system to realize bionic motions [15]. The modular robot is controlled by ANN method to realize deformation and form a powerful capture tool [18]. Most of soft modular robots are actuated by air pressure. Drag problem is greatly affect velocity and motion patterns of modular robot.

In this paper, we introduced a novel structure of soft modular robot, which has wireless controller and connected by magnetic force, to solve the drag problem of tubes. Moreover, the soft module connect with each other easily and fast. Therefore, the soft modular robot can form various configurations and different kinds of motion patterns. The design and manufacture of C-Balls robot module are introduced first in Section II. Section III illustrates mechanical analysis of soft modular robots, which are driven by magnetic force. Finally, Section IV discusses three kinds of experiments.

2. Design of C-Balls robot

The cost and robustness of modular robots become limiting factors when many soft modules are designed with modular systems. And most of modular robots have complex connecting parts. Therefore, C-Balls robot aim to address these issues by utilizing simplified mechanical structure and limited number of actuators.

The C-balls consist of two soft balls, which is utilized wireless controller to avoid the drag tubes problem, as shown in Figure. 1. Two soft balls are active module and passive module, which have characteristic of light weight of module. The weight of active module and passive module are 20 g and 10 g, respectively. Therefore, the light weight of module guarantee the C-ball moving ability, which is derived by friction forces between two modules.

![Figure 1](image1.png)

**Figure 1.** Structure of C-Balls robot, 1- soft shell, 2- gears, 3- magnetic wheels, 4- controller, 5- battery (3.7V, 40 mA), 6- shaft, 7- brushless DC motors(1230C), 6- braced frame.

The active module consists of soft shell and active actuator as shown in Figure. 1(a). The active actuator composed of gears, magnetic wheels, controller, battery, shaft, brushless DC motors and braced frame, which are putted inside of the soft shell. The active actuator has two brushless DC motors, which are used to actuate magnetic wheels respectively. And magnet wheels are fixed on shaft. The passive module has passive actuator, which consists of magnetic wheels and fixed shaft. Therefore, two modules are connected by non-contact magnetic force.

![Figure 2](image2.png)

**Figure 2.** The schematic diagram of control platform.
Both of the modules are used the same soft material shell, which is made from latex. Therefore, the modules have advantages are changeable size of shell via inflating air pressure and raising adaptive ability for environments. In addition, the structure of modules are designed simply, which can improve the stability of the system and reduce the cost of manufacture C-Balls robot.

The intelligent remote control system, including PC, remote-control handle (Xbox 1708), controller of active module, is established to realize control C-Balls robot motions. The schematic diagram of control system is shown Figure. 2. The controller of active module consist of motor driver, wireless receiver (2.4 GHz).

3. Dynamic analysis of C-Balls robot

In order to ensure connection of soft modules and C-Balls robot’s moving ability. The physical pivoting sphere model (PSM), which aim to analysis dynamic of C-Balls robot, is established. The dynamics analysis of C-Balls robot is shown in Figure. 3.

![Diagram of C-Balls robot](image)

**Figure 3. The static dynamics analysis of C-Balls robot**

Figure. 3 shows the longitudinal sections of C-Balls robot. And magnetic wheel A magnetic wheel B are wheels of passive module and active module, respectively. Two modules are connected by non-contact magnetic force between magnetic wheels.

The maximum static friction force between two modules can be expressed as follows,

\[ f_1 \leq F \cdot \mu_i \]  

Where, \( f_1 \) is the static friction force between two modules, \( \mu_i \) is the related frictional coefficients between shells, \( F \) is the magnetic force between two wheels, \( O_n \) is instant center of active module.

Therefore, C-Balls robot at static balance state when the force satisfied with conditions as follows,

\[
\begin{align*}
F + F_n &= 0 \\
Gd_1 + fd_2 &= 0
\end{align*}
\]  

Moreover, active module which needs external force, which is produced from actuator of active module, to realize forward motion. And the driven force is satisfied with condition as follows,

\[ M = M_1 + Gd_1 + fd_2 > 0 \]

Where, \( M \) is resultant moment of active module, \( M_1 \) is moment of active actuator.
The forward moving process of C-Balls robot is shown in Figure 4. The active module is rotated by driven moment. And friction $f_2$ between passive module and floor is smaller than friction $f_1$ between active module and floor, because of the weight of passive module is less than active module’s weight. Therefore, the passive module is push forward and the active module is driven by eccentric moment to move forward.

4. Experiments

To verify rationality of the soft modules’ structure and effectiveness of the wireless magnetic actuator, three types of experiments are performed on control platform. The experiments involve moving experiments, climbing experiments, and deforming experiments.

4.1. C-Balls robot moving experiments

C-Balls robot has two kinds of moving patterns, which are rolling and forward moving, as shown in Figure. 5 and Figure. 6. Active module and passive module are numbered module A and module B, respectively. Module B can roll on the surface of module B, which is driven by friction force between two modules. Therefore, magnetic force of modules, which is key element to bring friction force, is verified enough to guarantee C-Balls robot rolling movement.

Figure 5. Active module rolling on surface of passive module

Figure 6 illustrates C-Balls robot forward moving on the floor. Active module and passive module are numbered module A and module B, respectively. Friction force of module is bigger than module A’s friction force because of the weight of module B is heavier than module A. Therefore, C-Balls robot is driven by unbalanced friction momentum to move forward on the floor. And the moving velocity of C-Balls robot is 4.6cm/sec. Therefore, the moving ability of C-Ball is verified.

Figure 6. C-Balls robot forward moving on the floor
4.2. C-Balls robot climbing experiments

Figure 7 presents C-Balls robot climbing on two different kinds of material. C-Balls robot climbing on wooden block is shown in Figure 7(a). The module B is active module, and passive module is on the back of wooden block. Module B is driven by controller to move forward along vertical direction. Moreover, design of soft module’s structure is reasonable and reliable.

Figure 7(b) shows process of C-Balls robot climbing on soft fabric. The module B is active module, and passive module is on the back of wooden block. C-Balls robot is actuated by controller move downward along vertical direction. C-Balls robot can move on both hard material and soft material. Therefore, C-Balls robot has well adaptability to changeable environments.

4.3. C-Ball robots changing configuration experiments

C-Ball robots deforming experiments are shown in Figure 8. It illustrates the process of C-Ball robot from chained configuration to annular configuration. C-Balls Robots consist of three soft modules, including one active module and two passive modules. The active module is numbered module B, and the passive modules are numbered module A and module C, respectively.

5. Conclusion
In this paper, we design C-Balls robot whit a novel connection between modules and introduce the process for manufacturing the soft modules. The robot's outer skin is made from latex. Therefore, C-Balls robot has changeable size of shell to realize higher adaptation for environments. To achieve moving ability of the robot, non-contact connection of modules by magnetic force is designed and dynamic of modules is analyzed. We perform three types of experiments: moving on the floor, climbing on different materials, changing configuration.
Based on the current results, we will continue to research the motion of soft modular robots with different configurations. Therefore, the C-Balls module’s size is considered in the future work. Such work will enhance the adaptability of soft modular robots to environments.

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