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Development of a Transformable Mobile Robot Composed of Homogeneous Gear-Type Units

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Abstract

Recently, there has been significant research interest in homogeneous modular robots that can transform (i.e. reconfigure their overall shape). However, many of the proposed transformation mechanisms are too expensive and complex to be practical. The transformation process is also normally slow, and therefore the mechanisms are not suitable for situations where frequent, quick reconfiguration is required. To solve these problems, we have studied a transformable mobile robot composed of multiple homogeneous gear-type units. Each unit has only one actuator and cannot move independently. But when engaged in a swarm configuration, units are able to move rapidly by rotating around one another. The most important problem encountered when developing our multi-module robot was determining how units should join together. We designed a passive attachment mechanism that employs a single, six-pole magnet carried by each unit. Motion principles for the swarm were confirmed in simulation, and based on these results we constructed a series of hardware prototypes. In our teleoperation experiments we verified that a powered unit can easily transfer from one stationary unit to another, and that the swarm can move quickly in any direction while transforming.

1 Introduction

Mobile robots are often required to work in narrow and complex spaces - inspecting slender pipes, cleaning rooms that contain many obstacles, or searching for disaster victims in collapsed buildings. For a robot with a fixed external structure, the constraints imposed by these environments can make completing an assigned task difficult or impossible – the robot's size and shape prevents it from getting where it needs to go. An often-suggested solution is to miniaturize the robot. Doing so, however, may be infeasible or undesirable for two reasons: first, in many cases, the sensors, actuators and electronics required for a given task occupy a certain minimum volume, and second, efficiency may decline as a result of miniaturization. When vacuuming a dusty lab for example, covering the maximum amount of floor area per unit time is advantageous, implying that a suitable robot should be large. But if the floor is cluttered (and lab floors notoriously are), the robot needs to be small in order to effectively reach all the nooks and crannies. These competing demands can potentially be satisfied by a *transformable* robot, one that is able to dynamically change its shape.

A significant amount of research on transformable robots has been carried out. Based on their characteristics, transformable robots can be classified into three general categories:

I. snake-type robots,
II. modular robots that can rearrange their sub-units into different configurations, and
III. amoeba-type robots that have a freely-deformable external structure.

Hirose *et al.* have investigated Type I robots for some time. Beginning with snake configurations, their designs have evolved into articulated-body structures useful for work in nuclear reactors. Most recently, they developed the ACM, or Active Cord Mechanism, series of robots that are able to transform and move in three dimensions. Other researchers, including Yim *et al.*, have pursued work along similar lines [2-4]. A limitation of these designs, however, is that their transformation abilities are constrained by the need to attach to special 'docking'

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devices during the reconfiguration process.

Initial research on Type II systems began with a study of cellular robots by Kawauchi *et al.* [5]. They proposed a robot able to adapt to varying task content through the combination or separation of functional units. The units were not homogeneous, however, and not specially developed for mobility. There have been associated studies of self-repairing machines by Murata *et al.* [6-7], and reconfigurable robots by Chirikjian *et al.*, etc. [8-11]. The latest work in the area focuses on three-dimensional transformation and self-organization, although current prototypes change shape too slowly to be useful in real-world situations.

Yokoi *et al.* [12] have examined Type III, amoeba-like robots extensively. They use biology as an inspiration for their creations, developing a 'vibrating potential' method to enable deformation and movement in a multi-cellular amoeboid. Their hardware implementation, used to evaluate simulation results, has a number of drawbacks: once individual units (cells) are combined they are unable to separate, free-form transformation is not possible, and the transformation and movement processes are time consuming. In related research, Nakai *et al.* have studied deformable robots that utilize phase changes in low-melting-point metals [13]. Because of the nature of the approach, their robots also cannot deform or move quickly.

In this paper, we report on the development of a modular robot that is capable of moving and transforming at high speed, overcoming many of the limitations inherent in other designs. The robot consists of a swarm of homogeneous gear-type units. Each unit uses a single, simple actuator, and hence can be produced easily and cheaply. The four remaining sections of the paper follow. Section 2 describes the unit module and its actuator, while Section 3 explains our control algorithm and outlines some simulation results. Section 4 details experiments with an actual hardware prototype and discusses the passive magnetic attachment method used to maintain cohesion within a swarm. Section 5 gives conclusions and directions for future research.

2 A Transformable Mobile Robot Composed of Homogeneous Gear-Type Units

Our transformable robot has the following characteristics:

a. homogeneous modules,
b. a simple, inexpensive actuator for each unit, and
c. the ability to transform and move at high speed on a planar surface.

We use the terms 'unit' and 'module' interchangeably in the remaining portion of the paper. The complete robot consists of a group, or swarm, of at least two modules.

A conceptual view of several units is shown in Figure 1. Each unit contains a horizontally-mounted planar gear, with teeth around the unit's circumference. Multiple units can engage each other by interlocking their associated gears. A unit also has a one degree-of-freedom actuator, enabling it to rotate in the clockwise or counterclockwise direction. Although a unit cannot move independently, when engaged in a swarm configuration units are able move rapidly by rotating around each other. The gear-based interconnection mechanism prevents any slippage between the units during rotation.

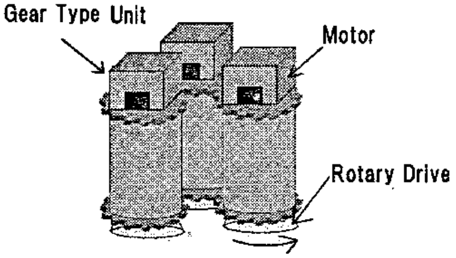


Fig. 1: A transformable mobile robot composed of homogeneous gear-type units

Figure 2 describes the proposed movement method used by the robot. The figure presents a top view of seven units. We assume that there is sufficient attractive force between units for the gears to effectively engage, and that enough friction is generated between each unit and the flat surface on which it rests to prevent units from being influenced by external, horizontally-applied forces. Consider the case where the swarm is required to move in the direction indicated by the bold arrow in step 1 – stationary units are white, while moving units are shaded. In step 2, we see unit *A* undergoing clockwise rotation, while unit *B* undergoes counterclockwise rotation. These rotations cause *A* and *B* to travel around the circumference of the stationary units, resulting in the translation of parts of the swarm (step 3). By repeating this process with different units, the entire swarm (robot) can move to a new position.

3 Simulation

3.1 The Simulator

In order to confirm the movement principles discussed in the previous section, we ran an extensive simulation on

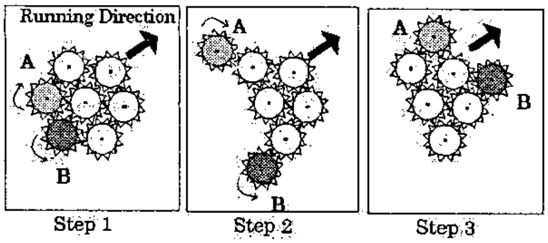


Figure 2: Movement method

a laboratory PC. To begin a simulation run, the user inputs the number of units, their initial configuration, and the final goal position for the swarm. The program then produces a top-view animation of the units' movements and the swarm's overall transformation and translation. Each circle in the simulator display represents one unit from the swarm. A single straight line between the center of a unit and its circumference is used to visually indicate rotary motion. An additional line is drawn between the center of a moving unit and its target position.

3.2 Control Method

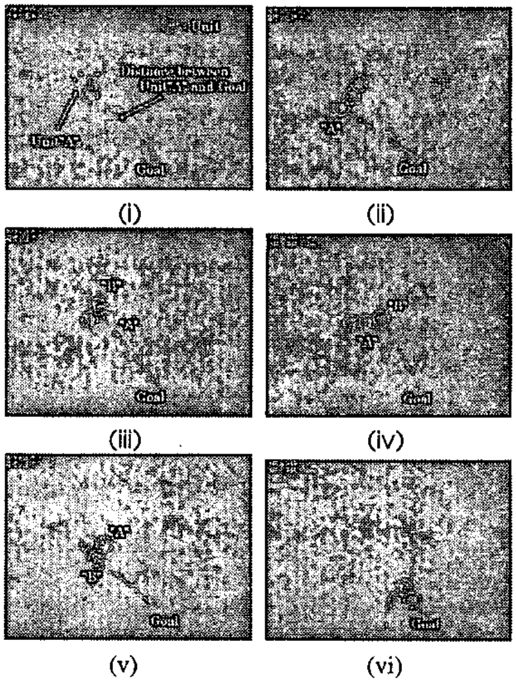
From the viewpoint of robustness and expandability, a decentralized control method is highly desirable. A large body of research on decentralized control exists, particularly in the area self-reconfigurable robotic systems [5-6, 12]. In our work, however, we used a centralized control strategy – our focus was on the mechanics of swarm mobility, rather than producing a robust control algorithm. We explain this control method below; more efficient and scalable control methods are considered part of possible future work.

An operator requests a final goal position and travel speed for the entire swarm, rather than for each individual unit. Units in the swarm move based on the following rule: the unit farthest from the goal position is always selected as the 'driven' unit (i.e. the unit whose actuator is powered), and only one unit is driven at a time. It revolves around an adjacent stationary unit in a direction that approaches the goal position. The unit stops moving when it makes contact with an additional stationary unit, at which time a calculation is performed and the next unit to be driven is selected.

3.3 Simulation Experiments

We implemented the control method described in 3.2 in our simulator application, making the assumption that in practice each unit would have all the functionality required to execute the described control algorithm. Our experiments involved a number of units ranging from two to ten. Each experiment was repeated ten times, with a random initial and goal position on each iteration. One experiment, using three units, is shown in Figure 3. Frame (i) shows the initial configuration, with the goal position in the lower right of the display. The unit farthest from the goal, labeled *A*, is selected as the first driven unit and revolves counterclockwise around an adjacent stationary unit (ii). After unit *A* is finished moving, unit *B* becomes the unit farthest from the goal. *B* therefore begins rotating in a clockwise direction (iv), moving until it makes contact with the second stationary unit (v). These steps are repeated until the goal position is reached.

The simulation experiments confirmed that the suggested transformation and movement algorithm is feasible. No problems were encountered when fewer than six units were involved in a simulation. However, we observed that a deadlock condition would frequently develop in simulations with more than six units. This means that the control method used is insufficient for situations requiring a large number of units. Again, we consider this an opportunity for future work.



(i) (ii)

(iii) (iv)

(v) (vi)

Fig.3: Simulation experiment

4 Hardware

4.1 Method Used to Generate Attractive Force Between Units

The most critical problem we encountered when developing our robot was determining how units should 'attach' to each other. We initially considered coupling units together using an encircling, fixed restraint, such as a chain. Although this idea is practical for a two-unit swarm, it becomes impossible to implement for three or more units. For example, Figure 4 compares two three-unit configurations: linear and triangular. The length of the shortest restraint that can be used to encircle all the units in the linear configuration is $2r(4 + \pi)$, while in the triangular configuration the length is $2r(3 + \pi)$. Since the required restraint length is dependent on the units' configuration, a swarm cannot be coupled together using a fixed-size chain.

To solve this problem, we investigated a second approach: using an elastic restraint similar to a bungee cord. However, increasing the number of units in the swarm increases the required restraint size. It is difficult to obtain an elastomer that is capable of accommodating a significant change in the required restraint length. Moreover, the units' movement capabilities can be adversely affected by the tension produced by an elastic restraint. As identified in Figure 5, it is somewhat of a misnomer to label the robot capable of "free transformation" when the presence of the restraint forces the overall external structure to be convex - even if the units' internal configuration is concave. We therefore determined that an external restraint is undesirable.

Finally, we investigated a method of coupling that uses the attractive forces supplied by magnets on each unit. However, the attachment problem cannot be solved using conventional, two-pole ring magnets. In this case, the polarity of the magnets can cause repulsive forces to arise in certain swarm configurations. Our ultimate solution employs a multi-pole magnet that has N and S poles peripherally and mutually positioned. Since the maximum number of units that can cluster around a given unit is 6 if all units have the same radius, we use a 6-pole magnet on each unit (see Figure 6). Using 6-pole magnets allows an attractive force to be produced between all units in any configuration. An additional benefit of this approach is that no articulated connecting devices are required to attach and separate units.

4.2 Prototype Implementation

We developed a prototype hardware implementation to verify our simulation results. A cross-section of the prototype is shown in Figure 7. The bulk of the each unit, which has a single actuator, is built from LEGO MindStorms components (e.g. gears). A unit measures 130 mm in height and weighs 280 g.

Each unit consists of a combination of two rotary platforms (diameter 55 mm) mounted one-above-the-other. Between the platforms is a gear with 56 teeth. In this implementation, only the bottom platform is able to rotate. A six-pole magnet (made by Neogium, Br: 1260-1310 mT, outside diameter 49 mm, inside diameter 30 mm, height 25 mm, weight 150 g) is also mounted between the platforms, forming a sandwich. One motor (running at 250 rpm) is placed at the center of the top of the unit. Its rotary motion is transmitted to the bottom of the unit via a central shaft. The motor, connected to a MindStorms RCX brick (8-bit, 16 MHz), can be made to rotate clockwise, counterclockwise and to stop.

We chose to construct three units, as this was the smallest number for which the circumference of the swarm changes depending on configuration. With three units, it is also possible to test the transfer of a moving unit from one stationary unit to another. When placed in close proximity, units automatically passively attach to each other due to magnetic attraction. As a unit's motor is powered up and the bottom of the unit begins to rotate, the frictional force with the floor surface decreases. A rotary torque on the adjoining stationary unit is generated, and the powered unit begins to roll along the circumference of the stationary unit. Since smooth movement cannot occur if the attraction between units is too strong, we carefully adjusted the magnetic force, decreasing the magnet's flux density by winding wire around the circumference of the magnet. In these experiments, 10 wraps of 1 mm wire were required to decrease the flux to a suitable level.

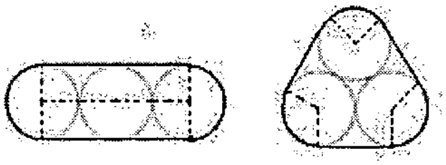


Fig.4: Circumferences of different configurations

Currently, it takes approximately 2.6 seconds for a driven unit to complete one rotation around a stationary unit. We purposely used a slow initial speed in our tests – theoretically, the rotation speed can be significantly increased, as long as a braking system is added. We believe that an ideal rotation period is about 1 second.

Given that our units do not require time for complex attach/detach procedures, we feel that our robot is capable of high-speed transformation and translation.

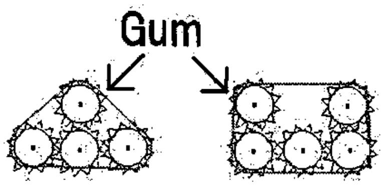


Fig. 5: Case of elastic restraint

In our experiments, we occasionally observed a situation in which a stationary unit would be dragged by a driven unit, or skidding of the driven unit would disrupt smooth transfers. The causes seem to be the lack of a braking system on each unit and the inaccuracies in our adjustment of the magnetic force to match the friction of the floor surface. Both of these problems should be addressed in future work.

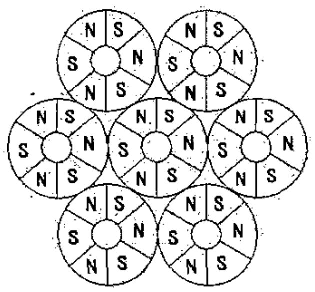


Fig.6: Peripheral 6-poles magnet

4.3 Motion Experiments

We carried out several basic experiments in order to confirm the operation of the prototype. We first tried a transfer experiment in which a driven unit moved from one stationary unit to another. Several frames from the video of the experiment are shown in Figure 8. Frame (i) shows the initial setup - unit *A* is driven, while units *B* and *C* are stationary. In (ii), *A* starts to rotate around *B*, making contact with *C* in (iii). As *A* continues to rotate, it loses contact with *B* and maintains a connection with *C* alone. In this experiment, we confirmed that a driven unit can successfully move from one stationary unit to another without special connecting devices or processes.

Our second experiment involved demonstrating that the swarm of three units was able move in a series of arbitrary directions. An operator chose the initial travel direction and then modified it on the fly using a joystick. We confirmed that the swarm was able to move as expected.

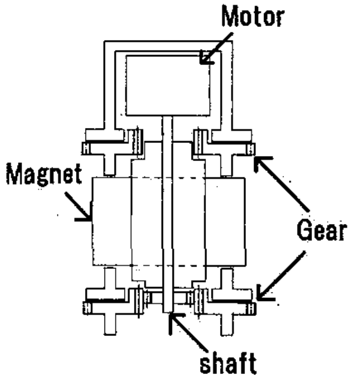


Fig.7: Cross-section of unit

5 Conclusion

In this paper we described the development of a transformable mobile robot composed of multiple gear-type units. We confirmed our proposed motion algorithm in simulation and through experiment. Specifically, we demonstrated that a moving unit can transfer from one stationary unit to another and maintain contact using a solely passive attachment mechanism. In our teleoperation experiments, three prototype units were able to transform and move quickly to a goal location.

The study was limited to an environment containing a flat surface with a suitable friction coefficient and no obstacles. In an actual task environment, the robot would likely encounter rough and uneven surfaces and obstacles. It is also possible that magnetic materials in the environment could influence the attractive force between units. We are presently considering these problems. Additionally, we would like to improve the hardware in each unit by adding a braking system and an online method for adjusting the magnet's coupling force. We have plans to make each unit self-sustaining through the addition of a battery and suitable sensors. We also plan to develop a decentralized control strategy for the swarm. Finally, we would like to evaluate the response of our system when more units are involved.

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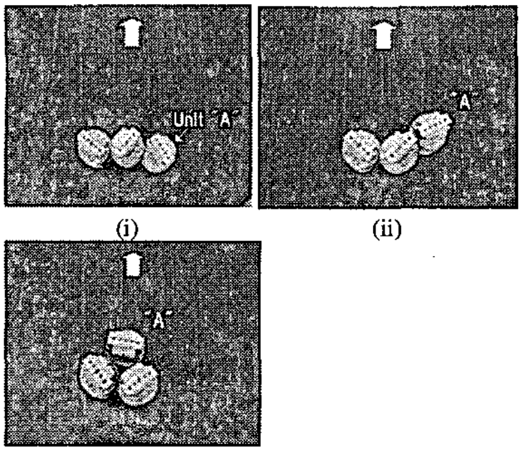

(i) (ii)

(iii)

Fig.8: Transfer between stationary units

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