A distributed modular self-reconfiguring robotic platform based on simplified electro-permanent magnets

Li Zhu

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A distributed modular self-reconfiguring robotic platform based on simplified electro-permanent magnets
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Abstract

Specialty: NETWORKS, TELECOM, SYSTEM AND ARCHITECTURE
Family name: ZHU
Given name: Li
Thesis delivered at: LAAS, UPS Toulouse
Title: A distributed modular self-reconfiguring robotic platform based on simplified electro-permanent magnets

A distributed modular self-reconfiguring robotic (MSRR) system is composed of many repeated basic modules with certain functions of motion, perception, and actuation. They can adapt to environment and goals by connecting and disconnecting to achieve the desired configuration and shape. MSRRs often contain two hardware systems: one is for actuation (motion), another one is for connection. At present time many institutions work on MSRRs; structural design, miniaturization, energy saving, control algorithms have been the focus of research in this area. However, only a few of them work on both the hardware and the corresponding algorithms. This thesis describes the design, fabrication, experimental results, distributed algorithm, and simulator of a MSRR platform. Via theoretical calculation and numerical simulation, we present the simplified electro-permanent (SEP) magnet which can change the magnetic field direction and does not require energy consumption while connected. A new concept of linear motor based on SEP is proposed. Then we construct DILI, a cubical MSRR, the length of each module is 1.5cm. DILI module can slide on a flat surface; the maximum speed can reach 20mm/s. With the new actuator, DILI can achieve the functions of motion and connection with only one system inside. Finally, a distributed algorithm is proposed in order to build a smart conveyor, and a simulator is designed that permits one to perform distributed simulations, test and validate distributed algorithms.

Keywords: Distributed computing, Modular robot, Smart System
Résumé

Spécialité : RESEAUX, TELECOM, SYSTEME ET ARCHITECTURE
Nom : ZHU
Prénom : Li
Thèse effectuée au : LAAS, UPS Toulouse
Titre de la thèse en français : Plate-forme robotique distribuée et auto-reconfigurable basée sur un aimant électro-permanent simplifié

Un système robotique distribué et reconfigurable (MSRR) est composé de plusieurs modules ayant certaines fonctions de mouvement, de perception et d'action. Ils peuvent s'adapter à l'environnement et aux objectifs en se connectant et en se déconnectant pour obtenir la configuration et la forme désirées. Les MSRR contiennent souvent deux systèmes : l'un constitué d'actionneurs pour le mouvement, l'autre pour la connexion. A l'heure actuelle, de nombreuses institutions travaillent sur les MSRR ; la conception, la miniaturisation, l'économie d'énergie, les algorithmes de contrôle ont fait l'objet de recherches dans ce domaine. Cependant, il existe peu d'études conjointes sur le matériel et les algorithmes correspondants.

Cette thèse décrit la conception, la fabrication, les résultats expérimentaux, l’algorithmique distribuée et un simulateur d'une plate-forme MSRR. En nous appuyant sur le calcul et la simulation numérique, nous présentons un aimant électro-permanent simplifié (SEP) qui ne consomme pas d'énergie lorsque le module est connecté à un autre module. Un nouveau concept de moteur linéaire basé sur les SEP est également proposé. Ensuite, nous présentons DILI, un MSRR cubique, de longueur 1,5cm. Le module DILI peut coulisser sur une surface plane, la vitesse maximale pouvant atteindre 20mm/s. Avec le nouvel actionneur, DILI peut réaliser les fonctions de mouvement et de connexion. Un module DILI peut se connecter avec quatre autres modules. Enfin, un algorithme distribué est proposé et un simulateur est conçu pour permettre de simuler le système distribué, de tester et valider les algorithmes distribués.

Mots-clés : Calcul distribué, Robot modulaire, Système intelligent
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Chapter I. General Introduction

This chapter presents the context of this study and significance of this thesis as well as the research work that has been done. This thesis was carried out in the Distributed Computing and Asynchronism (CDA) team of the Laboratory for Analysis and Architecture of Systems of National Center for Scientific Research (LAAS-CNRS), Toulouse, France with the funding of Chinese Ministry of Education.

I.1. Context

The first two industrial revolutions aimed essentially at increasing human productivity thanks to mechanization and use of steam engines (1760-1840) or electric motors (1860-1950). The third industrial revolution featured systematization and faster management thanks to automatic data processing via computers (1960-2010). Those three revolutions have changed the very nature of our societies, the way people work, live, communicate as well as organize themselves. The fourth industrial revolution that aims at the fusion of physical, digital world and the Internet (starting 2010) also promises important changes in the way people work and live. This revolution may lead to dramatic changes in the operation of companies and the factory of the future leading to more automatization, the cooperation of robotics systems and workers, flexibility and better adaptation to client’s demand.

Factory of the future will feature more efficient assembly lines like reconfigurable systems that can adapt to new goals or faulty situations in real time. This will lead to distributed, sustainable and economic robotic systems, like smart conveyors, which are an important part of the industry. Conveyors are usually designed as monolithic entities solving one problem at a time. They lack the flexibility to goals and environmental changes as well as robustness to failures that occur at small scale. To solve the problems, self-reconfigurable distributed modular robot systems are potential solutions, which are also new trends in robotics. The Smart Surface [1-3] and Smart Blocks [4-6] projects are two examples in this domain. The Smart Surface project gave rise to a unique concept of modular smart conveyor with distributed intelligence. The Smart Blocks project aimed at conveying and positioning fragile micro-parts by means of a dynamically reconfigurable distributed system consisting of modules with
Micro Electro Mechanical Systems (MEMS) that can move. This thesis is an extension of the Smart Blocks project, which aimed at building a distributed Modular Self-Reconfiguring Robotic (MSRR) system.

Since the year 1954, the world's first industrial robot UNIMATE invented by George Devol [7], the application of robot is no longer confined to workshop lines, factories. It has been used in hospitals, military industry, science and technology museums, entertainment venues, automobiles, textiles and homes and other places [8]. With the rapid development of science and technology, people have higher requirements for the automation and intelligence of robotics. Sometimes in order to take full advantage of resources, a robot is used to achieve different tasks, which requires the robot to quickly change its configuration to meet the requirements. Unfortunately, the mechanical structure of each robot limits what it can do. In addition, due to the risk that people may incur, more and more robots are applied in uncertain environments. However, in this kind of environment, it is difficult to determine the task of the robot in advance, and its working environment also has unpredictable conditions. Traditional robots are not capable of doing this because of their poor ability to adapt to changing circumstances and tasks. In view of the above problems, the researchers have put forward the theory of Modular Reconfigurable Robots (MRR) and modular self-reconfigurable robots (MSRR), which can also be called as modular self-reconfiguring robotic systems.

MRRs can change their shape and position by reorganizing the position and connection of the modules in the system. In a MRR system, a damaged module does not affect the overall normal operation; it can be replaced by other modules. Since the invention of the first MRR, more than one hundred kinds of MRRs have been invented.

MSRRs may have many applications. For example, they can be produced for the educational purpose. They can be used in smart manufacturing (like smart conveyors for drug manufacturing or tiny systems, e.g. clockwork manufacturing) or smart robots that evolve on difficult terrain. They can be used for programmable matter, e.g. furniture, tools, artworks.

So far, MRR systems are used in the lab as demonstrators or prototypes or in the education area. When designing a MRR, several principles need to be considered, for instance, the module should have a spatial symmetry that satisfies the motion requirements; the module should have sufficient freedom and drive capability (actuation); there must be a reliable connection between the modules; the moving
parts in the module must be able to be individually controlled; the modules should have data processing and communication capability.

On what concerns software aspect, MRRs are difficult to control. The control algorithm needs to match the structure of the modules, as the number of modules increases; the complexity of the algorithm also increases.

This thesis firstly presents a new type of actuator for distributed modular self-reconfiguring robotic (MSRR) systems. This actuator is based on simplified electro-permanent magnets, which can change its magnetic field direction and provide holding force without continuous power supply. A series of simulations have been made to figure out the impact of different parameters on the design of actuator.

Based on this actuator, we construct a new modular self-reconfigurable robot system. We call this cube-shaped modular robot system DILI, the length of each module is 1.5 cm. DILI can slide on a flat surface; the maximum speed can reach 20mm/s. With the new actuator, DILI can achieve the functions of both actuation (motion) system and connection system with only one system inside. A DILI module can connect with four other modules. The independent motion of a module also meets the rules of cellular automata.

Finally, a distributed algorithm and a simulator are designed for DILI. DILI is more like a platform, because of its structural and kinematic advantages; people can study complex robot design and algorithms based on it.

### 1.2. Contributions

This thesis completed the design and fabrication of a distributed modular self-reconfiguring robotic system. This system is a platform which presents the advantage of being easy to manufacture. The main work includes actuator design, actuator simulation, circuit design, modular robot structure design, conception of distributed algorithm, simulation software design.

In particular, the following work was done:

- Formalization of the new concept of simplified electro-permanent (SEP) magnet, which can change its polarity by a pulse current.
• Accurate design of the SEP magnet model with COMSOL Multiphysics and series of numerical simulations to observe the effects of different parameters. The numerical simulation results play a guidance role in designing and validating SEP magnet. Some laws of making SEP have also been summarized.

• The conception of a new type of linear motor (actuator), based on SEP magnet, and characterization of its performance. This linear motor can achieve both motion and connection with only one system; there is no energy consumption when modules are connected.

• Development of a dead-time controllable pulse circuit for the SEP magnet, and experimental verification.

• Construction of a new modular self-reconfigurable robot system: DILI, which can have 2D motion (four directions).

• Study of the performance of DILI robotic system through a series of experiments.

• Design of three capabilities of motion related to a possible load of a module, and proof of feasibility via experiments.

• Proposal of a distributed algorithm for controlling the motion of modules.

• Development of a simulation software for DILI modular robotic system that permits one to test and validate distributed algorithm.

I.3. Manuscript Organization

The structure of this thesis is shown in Figure I-1, details are presented as follows:

• Chapter II is a brief presentation of modular robot systems in state of the art. We then present a summary of the actuation and connection mechanisms and miniaturization methods of MRRs.

• Chapter III presents the theoretical design of a linear motor based on Simplified Electro-permanent (SEP) magnet. This new linear motor can achieve both motion and connection with only
one system.

- **Chapter IV** puts forward a series of numerical simulations of SEP magnet. These simulation results play a guidance role in designing and validating SEP magnet.

- **Chapter V** concentrates on the hardware design and fabrication of the circuit and the structure of DILI module. Experiments on real DILI modules are also given in this chapter.

- **Chapter VI** begins with the capabilities of DILI module. Afterwards, it presents a distributed algorithm for DILI. Finally, a simulator is presented, which allows people to test and validate distributed algorithms.

- **Chapter VII** summarizes the thesis, exposes the remaining questions to be addressed, and gives an outline of the subsequent work enabled by my research.
Chapter I
General Introduction

Chapter II
Related Works

Chapter III
New Concept of Linear Motor

Chapter IV
Design and Numerical Simulation of Simplified Electro-Permanent Magnet

Chapter V
Hardware Design: Circuit and Structure

Chapter VI
Distributed Control Algorithm and Simulation Software for DILI Robot System

Chapter VII
General Conclusion and Perspectives

Brief survey on MRR systems

Different classification

Connection mechanisms

Actuation mechanisms

Miniaturation methods

Motivation: Design and build a MSRR system with new connection and actuation mechanism. Design distributed algorithm and simulator for this MSRR system.

Theory and numeral calculations of EP magnet

Design the SEP magnet and a new linear motor (actuator)

Numerical simulation of SEP magnet

Circuit design for SEP magnet

Structure design for our MSRR system: DILI

Manufacture and test of circuit and DILI modules

MSRR: Modular Self-Reconfiguring robotic
EP magnet: Electro-Permanent magnet
SEP magnet: Simplified Electro-Permanent magnet

Figure I-1 Thesis structure
References in Chapter I


Chapter II. Related Work

In this chapter, we would like to present the general context, state of the art and proposed methodology of this thesis, which can help to clarify the current states, locate the PhD thesis in the correct context and have a global view of our work.

The purpose of this thesis is to build a modular self-reconfigurable robot system; the work is related to structure design, the actuation system, the connection system, miniaturization, distributed algorithm, and simulator. In the following sections, we present state of the art in these areas.

Section II.1 describes the background and the previous works. In Section II.2, we study some characteristics of modular robots; details on 121 modular robot systems are presented in this subsection. Section II.3 concentrates on two classifications of robotic systems; they are based on actuation mechanism and connection mechanism, respectively. Section II.4 deals with several methods for miniaturization, which is one of the challenges of modular self-reconfiguring robotic systems. Section II.5 concentrates on distributed algorithms and simulators for modular self-reconfiguring robotic systems. Section II.6 introduces the cellular automata and its application in modular self-reconfiguring robotics. Conclusions of this thesis are given in Section II.7.

II.1. The Smart Surface and Smart Blocks Projects

This work is an extension of the Smart Surface [1-4] and Smart Blocks [5-7] projects, which were funded by the French National Agency of Research (ANR) and that federated three French research laboratories and Japanese laboratory. The Smart Surface project gave rise to a unique concept of the modular smart conveyor with distributed intelligence which was essentially a static device. The Smart Blocks project aimed at conveying and positioning fragile micro-parts by means of a dynamically reconfigurable distributed system consisting of modules with Micro Electro Mechanical Systems (MEMS) that can move. It combined new results in microtechnology, control theory, and computer science to create a modular self-reconfiguring conveyor based on a contact-free technology. This conveyor is composed of centimeter-size blocks, called smart blocks that can connect in order to form a conveying surface. Each block also includes a MEMS actuator array in the upper face in order to move the objects.
II.2. Modular Reconfigurable Robots (MRR)

Nowadays, robotic systems have become an indispensable part of the human production process; many current human activities have been replaced by robots. In general, these robots are designed for specific-use according to the environment and mission requirements. At the beginning of the design, they are assigned a specific mission that is difficult to adapt to changes in the environment and goal.

It is a huge investment for redeveloping robots, and it takes a lot of time. In addition, people cannot accurately predict some of the working conditions in advance, and therefore a kind of robot which can change its own structure based on the environment and tasks is required. Thus, some principles which originally belonged to software engineerings like reusability and reconfiguration have been used in robotic hardware research. With the developing of electronic, MEMS and microsensor technologies, the processors, actuators, and sensors have become smaller and smaller. The control, actuation, connection and communication systems can be integrated into a single module. Then, with further researches, the initial simple Modular Robots gradually developed into Modular Reconfigurable Robots (MRR). MRR is composed of a large number of repeated basic modules with certain functions of motion, perception, and actuation. They can adapt to environment and goals by connecting and disconnecting to achieve the desired configuration and shape. For example, worm-like robots can pass through narrow holes, can cross the rugged terrain by transforming into quadruped robots, and also can form a ring-shaped configuration in a planar environment to achieve high-speed rolling motion [8]. Compared with traditional robots, MRR has the following characteristics: versatility, adaptively, extensibility, robustness, redundancy and low cost. According to the reconfiguration process, MRR can also be divided into Modular Manual Reconfigurable Robots (MMRR) and Modular Self-Reconfigurable Robots (MSRR). The former class requires manual participation. The biggest advantage of the MSRR is the adaptability, that is, MSRR can change their own configuration based on the environment, and achieve goal changes without external interference [9, 10].

The MRR concept can be traced back to the late 1980’s; it was first introduced by Toshio Fukuda at the Science University of Tokyo with the name CEBOT (an abbreviation for ‘cellular robotic system’) [11]. The size of CEBOT is 18x9x5cm; the weight is about 1.1kg. After more than 30 years of development, more than one hundred MRRs have been developed, they are different in shape and size, some weight a few kilograms (3D Unit is 7kg [12], ModReD is 3.17kg [13]), and some only weight a
few grams (Pebbles is 4g [14], Tribol is 3.7g [15,16]).

II.2.1. Applications of MRR

MRR has been studied in a number of areas, such as bionic, adaptive toolset, drug-delivery, inspection, rescue, exploration (satellite), mapping, and education and so on [17]. Figure II-1 gives an example of rescue application by M-TRAN [18]. M-TRAN can change its shape to achieve some tasks, such as locomotion in terrain through a four-legged gait, locomotion among debris through flow, supporting a beam, and to shelter survivors. Figure II-2 shows the Catoms [19] (in green, purple and blue). The Catoms collaboratively explore an unknown physical environment and inform a “macro” user through a data sink. Since groups of moving Catoms are able to share the map of the environment while transmitting it to the sink, a fast and detailed exploration of an unknown environment is facilitated [20].

Figure II-1 A rescue application by M-TRAN: (a) Locomotion in terrain through a four-legged Gait; (b) Locomotion among debris through flow; (c) Supporting a beam; (d) Shape formation to shelter survivors.
Figure II-2 Catoms scanning a complex environment: (a) Snapshot of the environment (rear view); (b) Snapshot of the environment (front view); (c) Example of a Catom escaping a cavity trap with backtrack; (d) Map overview at tick 14940.

In the field of education, two MRRs have been successfully commercialized: Cellrobot [21] and Cubelets [22] (see Figure II-3).

**Cellrobot.** Cellrobot is a spherical shaped MSRR that consists of two kinds of modules, one called “Heart” whose diameter is 88mm another one called “Cell” whose diameter is 80mm. Each module has eight joint faces which can be connected to each other through a simple twist movement. The joints will snap together for secure attachment. Cellrobot allows one Heart unit to be connected up to 20 Cells, including wheels and vision devices; each individual cell has a full 360-degree rotation. People can program and control Cellrobot through a smartphone.

**Cubelets.** Cubelets is a cubical shaped MSRR, which is designed for kids age 8 and up. Cubelets modules connect to each other through permanent magnets, these modules can be divided into three categories based on their functions:

- Sense blocks, this type of module is equipped with sensors for temperature, light, etc.;
- Think blocks, this type of module handles the information collected by the perceptual modules, which determines how the robot responds;
- Action blocks, this type of module is equipped with a motor or speaker and other devices.
Action modules receive instructions from the thinking modules and then respond. People also can program Cubelets via a computer.

II.2.2. MRRs from 1988 to 2017

We present now MRR. We counted 121 types of MRRs. Table II-1 gives details on these MRRs, the information about connection mechanism, actuation mechanism, architecture, shape, and Degree Of Freedom (DOF) is also given here. Sometimes we present several versions of some MRRs when they had an important revolution.
<table>
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<th>Architecture</th>
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Table II-1 Modular robots characterized by their connection and actuation
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II.3. Classification and State of the Art

MRR can be classified into various categories and subcategories, among which the widely accepted classifications are based on architecture, scale, locomotion, and structure. The categories based on architecture are the primary and best-known classifications. Murata and Kurokawa [8] studied the architecture of modular robots and formally classified their architecture into the chain, lattice, hybrid, and truss. Some examples of these architectures are shown in Figure II-4, which could give people an intuitive vision. Then, Gilpin and Rus [142] introduced free-form architecture in order to cover a few unique systems that do not fit into conventional architectures.

![Figure II-4](image)

Figure II-4 Some examples of modular robot architectures: (a) iMobot (hybrid) [102], (b) ATRON (lattice) [59], (c) YaMoR (chain) [80], (d) Odin (truss) [95], (e) Gear-Type Units (free-form) [56]

According to structure, MRR can be classified into linear, spatial, and planar. In linear structure,
there is no cross, no corner in the structure when modules connect to each other. This structure is mainly used in some snake-shaped or warm-shaped modular robots, such as ACM [35]. The plane structure is a kind of modular robots that can only move in the plane, such as Fracta [26]. Spatial structure means that the modular robots can move in three-dimensions, such as Tetrobot [31], TeleCube [50], M-TRAN [18] and SuperBot [72, 73].

On what concerns aspects related to composition, actuation and connection are two main systems of a MRR. Therefore, we classified the MRR according to these two properties, as shown in Figure II-5. Details will be given in the following two sub-sections.

![Figure II-5 Several classifications of MRRs](image)

**II.3.1. Classification via actuation mechanism**

In this section, the actuation attribute refers only to the actuation and transmission mechanisms
embedded in modules to enable gait locomotion, self-reconfiguration, self-assembly. Typically, actuators occupy more than 50% of the volume and weight of modules. We also note that actuation systems constitute major obstacles in downsizing modules [89].

When classifying MSRR based on actuation, we introduce the following classes: motor, manual and others (see Figure II-5). We detail now the different classes.

**Motor**

From the invention of modular robots to the present, the motor has been the most widely used actuation system. Furthermore, motor can also be subcategorized into brushless direct current (BLDC) motor like Telecube [50], PolyBot [45, 48], and Odin [95], brushed DC (BDC) motors like SMART [122], M3Express [124], and Roombots [99], stepper DC (SDC) motors like X-Cell [123] and ModRed [13], servo motor like CKBot [84].

**Manual**

In order to reduce the complexity of the controller and docking interfaces, some modular robots are sometimes assembled manually from an ensemble of different modules and connectors. They require human intervention at the time when reshaping of the morphology is desired. Since such kind of modular robots does not have to consider a complex actuation process, they are mainly designed to work with fixed topologies rather than for self-reconfiguration.

We stress that, even if this kind of modular robots is assembled manually, then they still may have the moving possibilities, GZ-I [93] is one example of modular chain robots with a manual configuration that can also achieve movement by cooperation.

**Others**

In addition to the motor and manual, with the development of materials science, sensor technology, there have been some interesting ways of actuation. Such as Shape Memory Alloy (SMA), pump, current, random movement, voltage and electro-permanent magnet.

**II.3.2. Classification via connection mechanism**

Connectors play a crucial role in modular robotics since they provide a key function between
modules. Based on Connection mechanism, MRR can be categorized into mechanical, magnet, others (see Figure II-5).

**Mechanical**

Mechanical can be subcategorized into the latch, gripper, key & lock, hooks, and treads (examples are shown in Figure II-6). These methods have a big advantage of stability and can provide strong connecting force; but they also have some drawbacks, such as the complexity of structure and response time is relatively long. These drawbacks limit their application in robots, especially at a small scale.

**Magnet**

Magnet connection methods contain the permanent magnet (Miche [85]), electro-magnet (Hexbot [121]), and Electro-Permanent (EP) magnet (Pebbles [14]). Permanent magnets can provide a tight connection between modules, but they require manual intervention which is contrary to the idea of autonomous robots. Electro-magnet is easy to control and act fast; however, the limit is that it requires a continuous power supply. EP magnet can also act fast and does not need continuous power supply during working, which is a new concept of connector for modular robots.

**Others**

Mechanical and magnet can be seen as the traditional connection methods. Some new methods have been used in recent years. In Stochastic Fluidic Robot system, Tolley et al. present a novel reversible module connection mechanism using a low melting point alloy which is soldered to a fluid environment [107]. Meanwhile, other methods such as Velcro (Simebot [74]), binder material (Soldecubes [132]), random movement (single-material [107]), pneumatic (Vaccubes [112]), electrodes (MEMS [78], where MEMS is here the name of a robot) have also been used in MRR. We summaries them into others due to the limited applications.
A qualitative comparison of several main connection methods for MRR can be seen in Table II-2. This table can provide a reference for choosing the connection method.
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<td>high</td>
<td>-</td>
<td>None</td>
<td>simple</td>
</tr>
</tbody>
</table>

Through the analysis of Table II-1, we get the trend of the development of connection methods from the year 1988 to 2017 (see also Figure II-7). Obviously, mechanical is the most widely used connection method, the ratio of magnet systems is increasing.

Figure II-7 Trend of the connection methods
II.4. Methods for Miniaturization

At present, most MRRs are in the research stage; they are rarely used in practical applications. One of the grand challenges of self-reconfiguring modular robotics is the assembly of a functional system from tens or hundreds of components. However, only systems comprised of small numbers of modules have been demonstrated. Miniaturization is one of the main reasons that stop MRR to be actually applied. One approach to scaling to large numbers of modules is to simplify module design by relieving the modules of the typical power, control, and actuation requirements necessary for locomotion like fluidic manipulation [107]. Scientists have made many attempts on this aspect. Therefore, some interesting design appears. There are three main methods for miniaturization.

II.4.1. Method 1: modules without actuation system

Since actuators occupy more than 50% of the volume and weight of modules, people developed some MRRs without actuation system. These MRRs are mainly used to study the communication between modules or control algorithms.

Miche. The Miche robots [85] (see Figure II-8 a) were invented by Kyle Gilpin, Keith Kotay, Daniela Rus at MIT. Miche robots are a set of robots that consists of 28 1.8-inch autonomous cube-shaped robots which are able to connect to and communicate with their immediate neighbors. Modules can disengage their magnetic couplings and fall away under the influence of gravity. Miche robots starting from an amorphous arrangement can be assembled into arbitrary shapes and then commanded to self-disassemble in an organized manner to form complex 3D shapes. When assembled into a structure, the modules form a system that can be virtually sculpted using a computer interface via a distributed process.

In addition to gravity, random movements are also often used for modular combinations as in the following examples:

Pebbles. The Pebbles [14] (see Figure II-8 b) is also developed by Kyle Gilpin and Daniela Rus’s team at MIT. With the assistance of external stochastic force which comes from a vibration table, Pebbles is capable of self-assembling into a uniform structure from a loose collection of disjoint modules. During the random movement, once a module meets with another one as desired, they will connect to each other
via electro-permanent magnets. Pebbles system forms an initial uniform grid of modules, and then subtracts the unnecessary modules until the goal structure is obtained.

**Single-material.** Michael T. Tolley and Hod Lipson at Cornell University [107] developed the Single-material system; it is composed of 15 mm scaled cubic modules which are made by 3D printing material. Single-material can assemble 3D target structures stochastically within a 1.3 litter assembly tank by manipulating the fluid flow at an active assembly substrate using external valving. The modules connect to each other by a mechanical structure and do not have any electronic equipment or power supply (see Figure II-8 c).

**Stochastic 2D and 3D.** P.J. White et al. also from Cornell University [65, 67] presented several modular robot systems in both 2D and 3D, all these robot systems do not have actuation system. The 2D system (see Figure II-8 d) has two prototype units, a square-shaped unit which uses electromagnets for connection and a triangle-shaped unit which use swivelling permanent magnets instead. The modules were shuffled randomly on an oscillating air table, when two modules collide properly, they bond one to another via the magnets, and release from each other if the configuration is not desired. The 3D system (see Figure II-8 e) uses electromagnets for connection, like Single-material robot, Stochastic 3D also moves thanks to the random fluid.

For the above modular robot systems, there are obvious drawbacks, they take time to reach the desired configuration, and they have a low success rate for configuration.
II.4.2. Method 2: substitution of the actuation system for an affiliate system

Automated Modular Assembly System (AMAS). Yuzuru Terada and Satoshi Murata at Tokyo Institute of Technology [76, 143] developed AMAS to simplify construction work by introducing modularity into both structural components and means of assembly. AMAS is mainly composed of cubical modules; the modules can connect to each other by mechanical hooks on their surface. The AMAS modules do not contain actuation system. Thus, an affiliated system whose name is assembler robot was introduced (see Figure II-9). The assembler robot with four degrees of freedom can walk on the modules by using an inchworm motion, repeating connection and disconnection actions. The assembler robot can carry a module with its hand (L shaped part). Thus, the assembler robot can construct nearly any structure by combining basic assembly actions.

Obviously, the limitation of this method is that it requires complex control algorithm.
II.4.3. Method 3: multi-system multiplexing

Catoms. Catoms robot [19] provides a good idea about miniaturization of robots. Catoms belong to Claytronics project carried out by Goldstein et al. at Carnegie Mellon University. Catoms is a series of cylindrical-shaped modular robots which had eight versions; the Planar Catom V8 is the newest one. The architecture of Catoms is free-form. The novel feature of Catoms is their ability to reconfigure (move) relative to one another without classical actuation methods presented in subsection II.3.1. Electromagnets are arranged around the robots, by controlling the state of electromagnets, a module can move and connect to other modules. Thus, one system can achieve both actuation and connection (see Figure II-10). This method is innovative; it can save size and weight. The drawbacks of Catoms are: the electro-magnets need a continuous power supply, and their cylindrical structure makes the movement tricky.
II.5. Distributed Algorithms and Simulators for MSRR

In this subsection, we deal with the different aspects related to control, distributed algorithm, software, and simulator of the reconfigurable modular robot. The reassembly process of MSRR has proven to be difficult to control because it involves the control of a distributed system with many mechanically coupled modules connected in time-varying ways [144]. Thus, a variety of distributed algorithms for MSRR has been developed.

In order to facilitate the task of programming ATRON, U. P. Schultz [145] presented a concept of distributed control diffusion: distributed queries are used to identify modules that play a specific role in the robot, and behaviours that implement specific control strategies are diffused throughout the robot based on these role assignments. Kamimura et al. developed both centralized and decentralized control method for M-TRANN III [90]. W M Shen et al. have presented a biologically inspired approach to distributed collaboration between the physically coupled modules for CONRO. This approach was used to accomplish global effects such as locomotion and reconfiguration [146]. Miao et al. [147] proposed a distributed algorithm for enveloping an object inside a hexagonal lattice environment based on local communications among neighboring modules and between modules and the lattice node containing a target object.

Julien Bourgeois’s team contributed a lot on distributed self-reconfiguration algorithm for cylindrical modular robots, such as Catoms. In 2014, they proposed a flexible distributed algorithm allowing the reorganization of a set of modular micro-robots into the desired target shape. Since their algorithm does not need an explicit description of the final shape, it shows a great flexibility concerning the range of target shapes [148]. In 2016, they proposed a parallel, asynchronous and fully decentralized
distributed algorithm to self-reconfigure robots from an initial configuration to a goal one. They also evaluated their algorithm at the millimetre-scale, which indicates that the number of communications, the number of movements and the execution time of their algorithm is highly predictable [149].

El Baz at LAAS-CNRS developed a distributed algorithm based on distributed election for establishing quickly a smart conveyor made of smart modules. This research work was done in the framework of the ANR Smart Block project [6].

Robert Fitch et al. present both centralized and decentralized algorithms for cubical MSRR, which plans module trajectories through the volume of the structure. They define free space by an arbitrarily-shaped bounding region. This addresses the important problem of reconfiguration among obstacles, and reconfiguration over a rigid surface [150]. By using this algorithm, they successfully simulated a transformation from a chair to a table (see Figure II-11).

Figure II-11 Example of simulation of reconfiguration for cubical MSRR

Meanwhile, many simulators for MRRs have been developed, such as Adam [151], Webots [152], OpenMR [153] (see Table II-3). These simulators allow people to create virtual environments for MRR, such as robots work on the surface of water [154], under the water [155] or on an air surface [156]. Simulators also allow people to visualize and debug in real-time, for example, VisibleSim permits one to test and visualize distributed algorithms in a 3D environment. As a consequence, simulators can not only facilitate the development of efficient algorithms but also can inspire hardware designers with innovative features [17].
II.6. Cellular Automata Theory Applied to MSRR

This subsection deals with a different approach based on cellular automata. We note that during the distributed control process of MSRR, the modules in the system could behave independently; in particular, motion plans can be made in parallel. In that case, the regular overall macro motion of the whole system results from the combination of local and concurrent module motions. Cellular automata have simple rules but can achieve complex movement, which can also provide a good reference for the distributed control of MSRR.

II.6.1. Cellular automata

Cellular automata (CA, single: cellular automaton) were introduced by Von Neumann in the 1940s; CA are discrete models studied in computability theory, mathematics, physics, complexity science, theoretical biology and microstructure modelling. CA are finite-state machines whereby each cell decides upon its next state based on its current state and the state of its neighboring cells [157]. The
two most common types of neighborhoods are the Von Neumann neighborhood (each cell has four neighbors) and the Moore neighborhood (each cell has eight neighbors), which is shown in Figure II-12.

![Von Neumann neighborhood and Moore neighborhood](image_url)

**Figure II-12 Different cellular automata neighborhoods**

### II.6.2. Applications to MSRR

Cellular automata have lacked during a long time a real representation in hardware as pointed out by Murata [26]. Then, in 2001 CA were first employed in developing distributed reconfiguration controllers by Butler Z., Kotay K. and Rus D. [158, 159]. They use a cellular automata model to create “water-flow” like locomotion. They assume that the robot moves on the floor and there are no obstacles. A set of eight rules are presented in Figure II-13, these rules are used to move a robot (represented as a rectangular array of cells) eastward. A module uses only one rule in each direction and plans its own motion at the next moment according to the environmental information on the neighbors and rules. For example, if rule 3 (see Figure II-13) is applied, then the result is that the current cell moves one unit in the eastward direction. Figure II-14 shows the modules across an obstacle by using the rules in Figure II-13. During the process, modules always keep the connection with each other, and no module is lost.

In 2003, Xu W. et al. [160] developed a set of rules for the class of planar lattice modules based on modules’ local perception about their immediate neighbouring lattice cells.

In 2004, Butler Z. et al. [159] devised a set of transition rules for realizing water-flow motion by MoleCube, M-TRAN, and Crystal modules, in which a modular robot is considered as a particular type of Cellular Automata which runs local rules in each individual cell. Local rule sets are based only on
the local configuration around a particular module, and consist of five and eight rules for water-flow in obstacle-free and obstacle-filled environments, respectively.

![Figure II-13 Rules for eastward locomotion with obstacles](image1)

![Figure II-14 Four snapshots of a simulation using the rule set in Figure II-13](image2)

In the same year, Kasper Stoy [161] proposed a seed-based self-assembly system in which gradients in the system were generated by seeds in order to produce growth in the system. Once gradient paths are generated, the automatically generated cellular automata (according to 3D CAD model description of the final configuration) are used to guide the growth process. Figure II-15 shows a Boing 747 is assembled from 9593 modules using Stoy’s self-reconfiguration algorithms.
In 2005, Wu Q. et al. [162] used CA for flow locomotion in the presence of obstacles by the M-Cubes lattice modules. In that work, the state of a cell is defined by the ID of modules located in front of its connectors and the next system state is computed by a transition rule generated by a two-layer artificial neural network with seven inputs (one for the cell state and six for states of neighboring cells) and one output (for the next state of the cell).

In 2012, Murata and Kurokawa [163] studied CA for generating the Flow operation based on an abstract model for a specific meta-module of M-TRAN called ‘tile’ model, in which a regular planar structure is considered as a plane filled with 2*2 tiles (cells). Their work considered these cells as objects of control (which are fixed in the environment) as opposed to conventional CA implementations that consider moving modules as control objects.

The above researches mainly focus on theory and lack practical application. The first step for applying the CA theory to MSRRs is to establish a MSRR that is suited to cellular automaton movement mechanism. For instance, for the block type ideal cellular automaton, the module of MSRR should have the connection ability between each other and can slide on their surfaces. Stoy and Kurokawa (see [164-166] for details) claimed that although several algorithms have been developed and validated based on their model, they have failed to be successfully deployed to the physical environment due to limitations in building reconfigurable robots that can satisfy necessary motion characteristics.
II.7. Conclusion

In this chapter, we have introduced modular robot systems along with their features, applications, and classification. In the physical composition aspect, actuation system and connection system are amongst the main parts of a modular robot. Three methods for miniaturization are detailed; these methods provide inspiration for the design of our MSRR. Contributions to the design of the distributed algorithms have been detailed. Cellular automata for controlling MSRRs have also been presented in this chapter. Although several algorithms have been developed and validated, people have generally failed to successfully deploy this algorithm to the physical environment due to limitations in manufacturing reconfigurable robots that can satisfy necessary motion characteristics.
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Chapter III. New Concept of Linear Motor

III.1. Introduction

As we have said in Chapter II, most actuators only have one function for connecting or moving; this chapter explores a new kind of fastenable linear motor for the smart distributed robot system. The organization of this chapter is as follows: Section III.2 introduces the Electro-permanent (EP) magnet and gives a brief introduction of magnetic materials. The mathematical calculation of the magnetic field of the solenoid will be given in section III.3. Section III.4 mainly talks about the new kind of linear motor which is based on a simplified electro-permanent magnet. Some experiments are discussed in section III.5. The conclusion is drawn in section III.6.

III.2. Electro-Permanent (EP) magnet

III.2.1. Magnetic Materials

There are two categories of ferromagnetic materials: hard and soft magnetic materials. A material in a magnetic sense is termed soft if the magnetization process is nearly reversible and hard if there is considerable hysteresis in the magnetization process. Soft magnetic materials are easily magnetized and demagnetized. They have the following characteristics: high magnetic saturation (saturation is the state reached when an increase in applied external magnetic field $H$ cannot increase the magnetization of the material further) [1]; low coercivity (also called the coercive force. For ferromagnetic material, the coercivity is the intensity of the applied magnetic field required to reduce the magnetization of that material to zero after the magnetization of the sample has been driven to saturation) [2]; high permeability (the degree of magnetization of a material in response to a magnetic field) [3]; low magnetocrystalline anisotropy (a ferromagnetic material is said to have magnetocrystalline anisotropy if it takes more energy to magnetize it in certain directions than in others) [4]; low core loss (in Alternating Current (AC) devices the magnetic core cause energy losses due to hysteresis and eddy currents (Foucault currents), this energy losses called core loss) [5] and high resistivity (resistivity is a fundamental property that quantifies how strongly a given material opposes the flow of electric current) [6]. Hard magnetic materials are difficult to magnetize and demagnetize. Compare with soft magnetic;
they have high saturation magnetization, coercivity, magnetocrystalline anisotropy and maximum energy product.

Now we concentrate on the Alnico5 [7] magnet and the NdFeB [8] magnet; their characteristics are the foundation of our work.

**Alnico5**

The primary composition of Alnico5 magnet is Aluminum (Al), Nickel (Ni) and Cobalt (Co), hence the name. Although it has a high remanent induction, it has relatively low magnetic values because of its easy of demagnetization. However, it is resistant to heat and has good mechanical features.

**NdFeB**

Known as the third generation of rare earth magnets, Neodymium (NdFeB) magnets are the most powerful and advanced commercialized permanent magnet today. Since they are made from Neodymium, one of the most plentiful rare earth elements and inexpensive iron, NdFeB magnets offer the best value in cost and performance. Comparing with other magnets, NdFeB magnets have higher remanence, higher coercivity, and lower $T_c$ (Curie temperature, the temperature at which the material loses its magnetism) than others.

NdFeB magnet has a very high coercivity, the Alnico5 magnet has a relatively lower coercivity (see Table III-1). However, both of them have about the same residual magnetism (see Table III-1, the residual magnetism is the magnetization left behind in a ferromagnetic material after an external magnetic field is removed, measured in Gauss or Tesla).

<table>
<thead>
<tr>
<th>Material</th>
<th>Residual magnetism</th>
<th>Coercivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>NdFeB</td>
<td>1.28 $T$</td>
<td>1120 kA/m</td>
</tr>
<tr>
<td>Alnico5</td>
<td>1.26 $T$</td>
<td>48 kA/m</td>
</tr>
</tbody>
</table>

**III.2.2. Electro-Permanent (EP) Magnet**

Electro-permanent (EP) magnet [9] is a solid-state device which allows an external magnetic field to be modulated by an electrical pulse. No electrical power is required to maintain the field. EP magnet
contains two magnetic materials, one magnetically hard and one semi-hard, capped at both ends with a magnetically soft material (e.g. Iron) and wrapped with a coil. Because of the characteristic of coercivity and residual induction, NdFeB (hard) and Alnico5 (semi-hard) are the two most common materials used to make the EP magnet. The coil can wrap the NdFeB magnet and Alnico5 magnet together or only wrap the Alnico5 magnet.

Figure III-1 details the principle of EP magnet. When current passes through the coil, the direction of the axial magnetic field of Alnico5 magnet changes with the direction of the current. When the magnetization direction of Alnico5 magnet is the same as NdFeB magnet, the external of magnetic flux reaches the maximum value. This correspondent to the ON configuration. When the magnetization direction of Alnico5 is opposite to that of NdFeB magnet, some or all the flux circulates inside the device; the external magnetic flux reaches the minimum value. This correspondent to the OFF configuration.

It is obvious that the EP magnet consumes power only when it changes the status to ON or OFF, otherwise, it does not need a power supply. Due to the energy saving characteristics, EP magnet can be used in some small-scale projects, such as Ara (Google module phone) [10] and Pebbles robot system (modular self-reconfiguring robotic system from MIT) [11]. Figure III-2 shows a module of Ara; the module can be locked and unlocked from the phone, each module fastens tight to the motherboard via EP magnet actuator. When users want to change a module, such as a camera module or a battery module, the circuit generates some pulses to release these modules. The EP magnet is shown in the red circle in Figure III-2.
Figure III-2 EP magnets in a Ara (Google modular phone) module

Figure III-3 presents the EP magnet which is used in Pebbles; it can hold up a 250g test mass. The magnetic rods are Grade N40SH NdFeB, and Cast Alnico5, both of them are 1.587mm in diameter and 3.175mm in length, and magnetized through their length. The pole pieces are Grade ASTM-A848 soft magnetic iron. An 80-turns coil is wrapped around the magnetic rods, the material of the coil is #40 AWG magnet wire with 390°C solder-strippable insulation [9].

Figure III-3 EP magnets on Robot Pebbles (MIT)
III.3. Analysis of Magnetic Field in the Solenoid

Section 2 has introduced the basic principle and structure of EP magnet. The most important part that we can learn is to change the direction of the magnetic field of Alnico5 with a solenoid. The magnetic field in the solenoid needs to be large enough, and greater than the coercivity of Alnico5. This section mainly analyzes the magnetic field within the solenoid [12, 13].

For tightly (without interval) wound infinite solenoid, the internal magnetic field is simple, it is a uniform magnetic field, and its direction is along the solenoid axis. It can be simply represented by the following formula:

\[ B_{in} = \mu_0 n I, \quad (3.1) \]

where \( \mu_0 \) is the vacuum permeability \( (\mu_0 = 4\pi \times 10^{-7} \text{ H/m}) \), \( \mu_0 \) is an ideal, (baseline) physical constant, which is the value of magnetic permeability in a classical vacuum, \( n \) is the number of turns along the axial in unit length, \( I \) is the current intensity in the solenoid in Ampere.

But in reality, there is no such a kind of infinite solenoid. So, we need to analyze the magnetic field of the non-tight-wound solenoid.

Figure III-4 presents a part of the solenoid. Assuming that the current is \( I \), the number of turns of the solenoid is \( N \), the radius is \( R \), the pitch is, and the number of turns along the axial in unit length is \( n = \frac{1}{d} \) (regardless of the diameter). Define the right-hand coordinate system as shown in Figure III-4, the origin (point \( O \)) of the coordinate is the point to be measured; the center axis of the solenoid is the x-axis; assume that a plane passes through the origin, perpendicular to the central axis, and intersects the solenoid at point \( Q \); y-axis passes through point \( O \) and \( Q \); the position of the z-axis can be obtained by the right-hand rule.
We take a line element $dl$ at point $P$ on the solenoid. The displacement vector from point $O$ to point $P$ is $\vec{r}$; the projection of the $\vec{r}$ in the $yz$ plane is shown by the dotted line in Figure III-4. The angle between the projection and the $y$-axis is $\beta$. Thus, the coordinates of point $P$ are:

$$
\begin{align*}
  x &= \frac{\beta}{2\pi} d = \frac{\beta}{2\pi n} \\
  y &= R \cos \beta \\
  z &= R \sin \beta
\end{align*}
$$

(3.2)

The individual components of $dl$ are:

$$
\begin{align*}
  dl_x &= dx = \frac{d\beta}{2\pi n} \\
  dl_y &= dy = -R \sin \beta \cdot d\beta \\
  dl_z &= dz = R \cos \beta \cdot d\beta
\end{align*}
$$

(3.3)

From Biot-Savart Law, the magnetic induction intensity at the point $O$ is:
\[ B = \frac{\mu_0 I}{4\pi} = \frac{1}{\pi} \int_{\Omega} \frac{\hat{d} \times \hat{r}'}{r'^3} \]  

(3.4)

where \( \hat{r}' \) is the displacement vector from point \( P \) to point \( O \), \( \hat{r}' = -\hat{r} \), \( P_1 \) and \( P_2 \) are the left and right endpoints of the solenoid, respectively. In order to get the components of the magnetic induction intensity at the point \( O \). We firstly calculate:

\[
\begin{align*}
(d \hat{I} \times \hat{r}')_x &= r'_x dl_y - r'_y dl_x = R^2 \cdot d \beta \\
(d \hat{I} \times \hat{r}')_y &= r'_x dl_z - r'_z dl_x = \frac{R}{2\pi n} (\sin \beta - \beta \cos \beta) \cdot d \beta \\
(d \hat{I} \times \hat{r}')_z &= r'_y dl_z - r'_z dl_y = -\frac{R}{2\pi n} (\cos \beta + \beta \sin \beta) \cdot d \beta
\end{align*}
\]

(3.5)

\[ r = \sqrt{x^2 + y^2 + z^2} = \frac{1}{2\pi n} \sqrt{(2\pi nR)^2 + \beta^2} \]  

(3.6)

Then, combining (3.4), (3.5), and (3.6), we can get:

\[
\begin{align*}
B_x &= \frac{\mu_0 I}{4\pi} (2\pi n)^3 R^2 \int_{\beta_1}^{\beta_2} \frac{d \beta}{[ (2\pi nR)^2 + \beta^2 ]^{3/2}} \\
B_y &= \mu_0 I n^2 R \int_{\beta_1}^{\beta_2} \frac{\sin \beta - \beta \cos \beta}{[ (2\pi nR)^2 + \beta^2 ]^{3/2}} d \beta \\
B_z &= -\mu_0 I n^2 R \int_{\beta_1}^{\beta_2} \frac{\cos \beta + \beta \sin \beta}{[ (2\pi nR)^2 + \beta^2 ]^{3/2}} d \beta
\end{align*}
\]

(3.7)

Assume distance between the midpoint of one circle of the solenoid and point \( O \) is \( b \). The azimuth angles of point \( P_1 \) and \( P_2 \) are:

\[
\begin{align*}
\beta_1 &= \frac{N}{2} 2\pi - \frac{b}{d} 2\pi = -N\pi - 2\pi bn \\
\beta_2 &= \frac{N}{2} 2\pi - \frac{b}{d} 2\pi = N\pi - 2\pi bn
\end{align*}
\]

(3.8)
Put formula (3.8) into formula (3.7); we can get the distribution of magnetic field in the solenoid:

\[
B_x = \frac{1}{2} \mu_0 n I \left( \frac{N}{2n} - b \right) \left( \frac{N}{2n} + b \right) \left( \frac{R^2 + \left( \frac{N}{2n} - b \right)^2}{R^2 + \left( \frac{N}{2n} + b \right)^2} \right) \\
B_y = \mu_0 I \pi n^2 R \int_0^\beta \frac{\sin \beta - \beta \cos \beta}{\left( 2\pi n R \right)^2 + \beta^2} d\beta \\
B_z = -\mu_0 I \pi n^2 R \int_0^\beta \frac{\cos \beta + \beta \sin \beta}{\left( 2\pi n R \right)^2 + \beta^2} d\beta 
\]  
(3.9)

When the solenoid is infinite, that is \( N \to \infty \), the magnetic field in the infinite solenoid is:

\[
\beta_x = \mu_0 n I \\
\beta_y = 0 \\
\beta_z = -\mu_0 n I \left[ 2\pi n R k_0 (2\pi n R) + k_1 (2\pi n R) \right] 
\]  
(3.10)

where \( k_0(t) \) and \( k_1(t) \) are the zero derivative and the first derivative of the second kind of deformed Bessel function.

When the solenoid is tightly wound, that is \( n \to \infty \), due to \( K_0(2\pi n R) \to 0 \) and \( K_1(2\pi n R) \to 0 \), we can get the magnetic field as follows:

\[
\begin{align*}
B_x &= \mu_0 n I \\
B_y &= 0 \\
B_z &= 0 
\end{align*} 
\]  
(3.11)

The above calculation only considers a solenoid with limited length. In fact, the Alnico5 inside the solenoid also has an effect on the magnetic field. Moreover, the applied current will be a non-linear pulse current, which will also make the calculation process more complex. Therefore, this calculation is only for reference; Chapter IV will detail numerical simulations via software like COMSOL.
Multiphysics.

III.4. Linear Motor Based on Simplified Electro-Permanent (SEP) Magnets

For EP magnets, due to their small power consumption, they are primarily used to provide a force to fasten objects. This section will introduce a new concept of the linear motor (actuator) that contains both motion and connection functions. The linear motor is composed of simplified electro-permanent (SEP) magnets.

III.4.1. Principle of Simplified Electro-Permanent (SEP) magnet

The main principle of SEP magnet is shown in Figure III-5. The Alnico5 is wrapped by the copper coil; its magnetic field direction can be changed when a positive pulse or a negative pulse passes the coil. Note that magnetic field also changes with polarity, for a facility of the presentation we emphasize on polarity change. It is not difficult to see that this principle is similar to the EP magnet, the difference is that the Alnico5 magnet is not placed in parallel with NdFeB magnet, and there is no soft magnet part. Since the structure of this new type actuator is only a part of the EP magnet, thus, we call it SEP magnet, where S means simplified.

![Figure III-5 The principle of SEP](image-url)
III.4.2. Motion and connection mechanisms

Figure III-6 displays an example of motion mechanism of SEP magnets. According to the basic principle of the magnets, the same polarities repel themselves, and different polarities attract themselves. As shown in this figure, there are two SEP magnets; one produces repulsive force, another one produces attractive force at the same time; thus, the permanent magnet NdFeB can be moved by the magnetic field. Figure III-6 is just a schematic diagram, in a real situation (see chapter V), the two kinds of magnets are embedded in a cube. Thus, the permanent magnet will not roll. Since SEP magnets are controllable, the direction of movement is also controllable. In fact, the two SEP magnets and the permanent magnet combine into a new concept of the linear motor. In this linear motor, the SEP magnets are the stator; the NdFeB magnet is the rotor. We note that the NdFeB magnet also can be the stator; in that case, the SEP magnet becomes the rotor relatively.

Besides motion, there is a fastening force when Alnico5 magnet and NdFeB magnet have different polarities. Thus, this linear motor naturally contains a function of connection.

![Figure III-6 Motion mechanism of new linear motor](image)

Figure III-7 displays a series of motion and the status of magnetic field of SEP magnets. The NdFeB (rotor) moves from right to the left. The initial polarity of NdFeB and SEP magnets are the
same. At each step, only one SEP magnet need to change its polarity. There is only one permanent magnet in Figure III-7, but the rotor can be composed of a plurality of permanent magnets.

![Figure III-7 Status of magnetic field of SEP magnets in motion](image)

Except for providing both driving force and fastening force, the new linear motor can move in any direction, with the proper arrangement of permanent magnets or SEP magnets in the plane. Figure III-8 and Figure III-9 give two examples of using this actuator to achieve circular motion. As shown in Figure III-8, we assume that the initial magnetic field directions of NdFeB magnet, No. 0 SEP magnet and No. 7 SEP magnet are the same. The NdFeB magnet can have circular motion when changing the direction of the magnetic field of SEP from No.1 to No.7 in turn. The NdFeB magnet can also have circular motion in the opposite direction by changing the direction of the magnetic field of SEP magnet from No.7 to No.1 in turn.

As mentioned before, both SEP magnet and NdFeB magnet can be the stator and the rotor. This provides a great convenience when designing the structure of the robot. If we need to simplify the motion structure and do not even contain any circuit, we can set the NdFeB magnet as a rotor, just as shown in Figure III-8. But if we want to save costs and reduce the difficulty of the control system, we can design the structure as shown in Figure III-9. In this example, we only need to control two SEP magnets rather than eight. Since we need to control the movement direction, we need at least two SEP magnets to be the rotor. The possibilities of motion are shown in Figure III-10. As can be seen, the more intensive SEP magnets are arranged, the more possibilities of the movement direction.
Figure III-8 Circular motion, NdFeB is the rotor

Figure III-9 Circular motion, SEP is the rotor

Figure III-10 Possibilities of motion
III.4.3. Enhanced magnetic field

Compared with the normal electromagnet and EP magnet, the advantages of SEP magnets are obvious: SEP magnets can achieve both motion and connection functions. Besides them, another advantage of SEP magnets is the possibility to have another mode that is the enhanced magnetic field. As shown in Figure III-11, when small electric current passes through the coil of the SEP magnet, the coil becomes an electromagnet. When the direction of the magnetic field of the electromagnet coincides with the direction of the magnetic field of Alnico5 magnet, the magnetic field shown by the entire SEP magnet will be enhanced as shown in this figure. Thus, the motion speed and the connection force between the two kinds of magnets are enhanced. But this function also consumes more power, generates heat and reduces the life of the system, so this function is only recommended when large adsorption forces (such as vertical motion and carrying objects) or when quick movements are needed.

![Figure III-11 Principle of enhanced magnetic field](image)

III.5. Fabrication of a SEP Magnet and Tests

We make a simple SEP magnet to test its characteristics. The Alnico5 magnet is 8mm in length, 3 mm in diameter, and wound around by a 360-turn coil. We use the pulse generator to produce rectangular pulses, the amplitude of each pulse is 9.2 volt, and the width is 400 microseconds. Figure III-12 presents
the result of the test. In the beginning, no pulse passes through the SEP magnet, and then we separate the two magnets. After passing 10 pulses through the SEP magnet, the polarity of Alnico5 is changed. Then we change the direction of NdFeB magnet (which can be seen via the white mark on NdFeB magnet) and put it close to SEP magnet. The SEP magnet and NdFeB magnet attract each other, which means the SEP magnet is reversely magnetized by pulses. Otherwise, the NdFeB magnet will be excluded away. This test validates our design of SEP magnet. In theory, SEP magnet can be made as tiny as possible.

![SEP magnet and NdFeB magnet](image)

Figure III-12 Alnico5 magnet reversely magnetized

### III.6. Conclusion

This chapter is mainly a presentation of the concept of SEP magnet. SEP magnet is a simplified EP magnet; its principle can be described by analyzing the magnetic field in a solenoid. SEP magnet can be used in a linear motor, which can achieve both moving and connection with only one system and does not require energy consumption while connected. By using this concept, the complexity of the structure of modular robot systems can be greatly reduced; the size of the robot modules can also be greatly reduced; moreover, this motor can save energy, which is very important especially for robots at a small scale.
References in Chapter III


Chapter IV. Design and Numerical Simulation of Simplified Electro-Permanent Magnet

IV.1. Introduction

In Chapter III we have introduced the principles of SEP magnet, but we did not give details on the value of the different parameters in order to build a SEP magnet with low power consumption, small size, strong connecting force and strong driving force. This chapter aims at validating our design and finding the most reasonable parameters of the SEP magnet such as the number of coil turns, coil coverage area, copper wire diameter, current size and so on.

Section IV.2 presents the hysteresis loop and the whole process of the polarization change in the SEP magnet. Section IV.3 details the Jiles-Atherton model, which is used in the numerical simulation model. The design of the model and numerical simulation via COMSOL Multiphysics are presented in section IV.4. Section IV.5 discusses the effect of some important parameters like the number of coil turns and coverage area of the coil in the model. The conclusion of this chapter is given in section IV.6.

IV.2. Hysteresis Loop

Magnetic hysteresis is an inherent characteristic of some materials; it occurs when an external magnetic field is applied to a ferromagnet (such as the iron), and the atomic dipoles align themselves with it. Even when the field is removed, part of the alignment will remain, which means the material has become magnetized. Once magnetized, the magnet will stay magnetized indefinitely. It requires heat or a magnetic field in the opposite direction in order to demagnetize the magnet [1].

The relationship between field strength $H$ and magnetization $M$ is not linear in these materials. If a magnet is demagnetized ($H=M=0$), the relationship between $H$ and $M$ is plotted for increasing levels of field strength, $M$ follows the initial magnetization curve. This curve increases rapidly at first and then approaches an asymptote called magnetic saturation. If the magnetic field is now reduced monotonically, $M$ follows a different curve. When the strength becomes zero, the magnetization is offset from the origin by an amount called the remanence. If the $H$-$M$ relationship is plotted for all values of the magnetic field, the result is a hysteresis loop called the main loop. The width of the middle
section along the $H$ axis is twice the coercivity of the material [2].

Figure IV-1 describes the limit hysteresis loop, that is, the largest one of all hysteresis loops. In the beginning, at point $o$, the ferromagnetic material is in the magnetic neutral state ($H=0=B=M=0$). When the material is placed in the external magnetic field $H$, the material begins to magnetize; the curve travels along $o-b$. When reaching the saturation state (point $a$), the magnetization intensity $M$ is at the saturation value $M_s$ and no longer increases with the increase of the magnetic field strength $H$; the curve starts parallel to the $H$ axis and extends to point $b$, and the curve $o-a-b$ is the starting magnetization curve. When the magnetic field strength $H$ starts to reduce, since the change of magnetization intensity $M$ is lag the change of magnetic field strength $H$, the magnetization intensity curve returns not in accordance with the original path but along the curve $a-c-d-e$. When the magnetic field strength $H$ is reduced to zero, the intersection of the curve and the $M$ axis is the residual magnetization intensity, $M_r$. By adding an opposite magnetic field $H_c$, the magnetization $M$ could be reduced to zero, $H_c$ is a coercive force.

When the reverse magnetic field strength reaches $H_s$, the material will reach the saturation state (point $d$) in the opposite magnetize direction. In this case, the corresponding magnetization $M$ is $-M_s$. If $H$ is increased at this time, the curve will reach the positive saturation state according to the path $d-f-g-a$. The curve $a-c-d-f-g-a$ constitutes a closed hysteresis loop, this hysteresis loop is an irreversible magnetization process, and one $H$ value corresponds to two $M$ values. Curve $a-b$ and $e-d$ are reversible magnetization processes.
In order to accurately express the magnetization properties of ferromagnetic materials, it is necessary to handle their various magnetization curves and hysteresis loops correctly. Nowadays, the study of the hysteresis loop theory and its model building method is described in the literature. The Jiles-Atherton (J-A) [3-5], Preisach [6] and Stoner-Wohlfarth (S-W) [7] are three classical models in magnetization modelling. The advantages and disadvantages of the above four models in the simulation of ferromagnetic materials are described systematically by [8]. Jiles-Atherton (J-A) model was introduced by D.C. Jiles and D.L. Atherton in 1983. This model passed through the experimental verification, and has been widely used for practical applications. Based on the Weiss ferromagnetism theory [9], it requires a wide magnetic field for a ferromagnetic material to reach saturation magnetization from the initial state. In this magnetic field, there is a strong interaction between the atomic moments of the ferromagnetic material, which tends to rotate to be parallel to each other. The role of the external magnetic field is only to change the magnetic direction of the formation of spontaneous magnetization. Weiss names this strong internal range as ferromagnet to be magnetized from the initial magnetization to saturation magnetization. In a magnetic field as a molecular field \( H_m \), and assume that the expression is \( H_m = aM \), where \( a \) is the molecular field.
parameter, $M$ is the magnetization intensity. If the direction of the external magnetic field is parallel to the direction of the magnetization, then the effective magnetic field inside the ferromagnetic is:

$$H_e = H + H_m = H + aM$$  \hspace{1cm} (4.1)

Then according to the paramagnetic magnetization theory and the definition of Langevin function $L(z)$, we can get:

$$M(z) = M_s L(z) = M_s \coth(z - \frac{1}{z})$$  \hspace{1cm} (4.2)

where $M_s$ is the saturation magnetic polarization intensity, which is often provided by the manufacturer, $M_s = Nm$ and $N$ is the number of molecules per unit volume; $m$ is the modulus of the atomic magnetic moment; $z = He/a$, $a = kT/m$, where $k$ is the Boltzmann constant, $T$ is the temperature of the material (in unit Kelvin).

We replace $M$ in the formula (4.2) by $M_{an}$; then the equation can represent the relationship between the magnetization and the external magnetic field strength during the ideal magnetization of the ferromagnet. $M_{an}$ is called the non-hysteresis magnetization. According to formula (4.2), if the value of external magnetic field strength is given, $M_{an}$ can be uniquely determined.

Jiles-Atherton hysteresis model is based on the above Weiss molecular field theory. The hysteresis of ferromagnetic materials is described by a set of differential equations which can be expressed as a full differential magnetic susceptibility:

$$\frac{dM}{dH} = \frac{(1-c) dM_{irr} / dH_e + c dM_{an} / dH_e}{1 - \alpha c dM_{an} / dH_e - \alpha (1-c) dM_{irr} / dH_e}$$  \hspace{1cm} (4.3)

where $H$ is the magnetic field strength, $M_{an}$ is the modified Langevin function:

$$M_{an}(H) = M_s \left[ \coth \left( \frac{H_e}{a} \right) - \frac{a}{H_e} \right]$$  \hspace{1cm} (4.4)

Formula (4.3) can be used to describe the non-hysteresis magnetization; $M_s$ is the saturation magnetization; $M_{irr}$ is the irreversible magnetization; $M_{rev}$ is the reversible magnetization; the total magnetization $M$ equals to the sum of $M_{irr}$ and $M_{rev}$; $c$ is related to the ratio $M_{rev}/M$; $H_e$ is the effective
field strength of the material,

\[ H_e = H + \alpha M \]  \hspace{1cm} (4.5)

where \( \alpha \) is the material-related parameter; the total magnetization \( M \), the relationship between \( M_{\text{irr}} \) and \( H_e \) is as follows:

\[ \frac{dM_{\text{irr}}}{dH_e} = \frac{M_{an} - M_{\text{irr}}}{k\delta} \]  \hspace{1cm} (4.6)

\[ M = M_{\text{irr}} + c \left( M_{an} - M_{\text{irr}} \right) \]  \hspace{1cm} (4.7)

where \( k \) quantifies average energy required to break pinning site in the magnetic material, \( \delta \) depends on the direction of changes of magnetizing field \( H \) with \( \delta = 1 \) for increasing field, \( \delta = -1 \) for decreasing field.

When the magnetization is known, the corresponding magnetization value can be known by calculating the formula (4.3). In the formula (4.3) - (4.7), there are five parameters: \( a \), \( \alpha \), \( M_s \), \( k \), and \( c \). The characteristics of the magnetic material are uniquely determined by a set of five parameters.

These parameters have different effects on the shape and size of the hysteresis loop [3]:

- \( M_s \) only affects the highest point of hysteresis loop, with the increase of \( M_s \), the highest point of hysteresis loop is also increasing;

- \( \alpha \) affects the inclination of knee part (\( c-d \) in Figure V-1) of hysteresis loop, the greater the value, the steeper the knee;

- \( a \) affects the inclination of hysteresis loop, including the knee part, the greater the value, the gentler the hysteresis loop;

- \( k \) affects the coercive force, the larger the value, the wider the hysteresis loop;

- \( c \) affects the slope but does not affect the knee part, the greater the value, the gentler the hysteresis loop.

In the simulation process, we have adjusted the above five parameters in order to calibrate the
hysteresis loop of Alnico5. This will be shown in the sequel of this chapter.

**IV.4. Numerical Simulation with COMSOL Multiphysics**

COMSOL Multiphysics is a numerical simulation software for engineering. It originated in the Toolbox of Matlab, originally named Toolbox 1.0. Then it was renamed as Femlab 1.0 (FEM for the finite element, LAB is taken from the Matlab), the name has been used to Femlab3.1. Since version 3.2, COMSOL Multiphysics become its official name [10].

COMSOL Multiphysics can achieve direct coupling of multi-physics fields. Due to its superior multi-field direct coupling capability and efficient analytical and computational power, it has been universally accepted and widely used in the domain of numerical simulation. COMSOL Multiphysics offers a variety of modules for different areas, including AC/DC, microelectromechanical systems, RF, acoustics, chemical engineering, geoscience, structural mechanics, and so on. We mainly use the AC/DC module in our work.

**IV.4.1. Model**

In the sequel, we present simulation results of SEP magnet with COMSOL 5.2 [11]. Since the structure of the SEP magnet is axisymmetric, we only need to establish a two-dimensional symmetric model, which is shown in Figure IV-2. The model consists of three parts, the first part is Alnico5 (see Figure IV-3 (a)), it has a size of 1.5mm * 8mm; the second part is a copper coil, with an initial size of 0.7 * 10mm (see Figure IV-3 (b)), its size is changeable; the third part is air (see Figure IV-3 (c)).
Figure IV-2 2D domain of the numerical simulation including Alnico5, coil and surrounding air

Figure IV-3 Three views at SEP magnet model: (a) Alnico5, (b) Copper, (c) Air
IV.4.2. Physical parameters

The definition of physical parameters includes the definition of material properties and the setting of boundary conditions and initial values. When the model contains multiple subdomains, and their physical parameters are not the same, we also need to define the physical parameters for each subdomain. In order to simplify the simulation experiment, we use parametric modelling, that is, the whole simulation can be controlled by some global parameters, these parameters include geometric parameters, operating parameters, coil parameters, condition parameters, solver parameters, material parameters. Table IV-1 shows the parameters of the entire simulation model in COMSOL.

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Initial Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>1.5[mm]</td>
<td>0.0015 m</td>
<td>Geometric parameters: the radius of Alnico5</td>
</tr>
<tr>
<td>Length</td>
<td>8[mm]</td>
<td>0.008 m</td>
<td>Geometric parameters: the length of Alnico5</td>
</tr>
<tr>
<td>R_coil_in</td>
<td>1.8[mm]</td>
<td>0.0018 m</td>
<td>Geometric parameters: the inside diameter of coil</td>
</tr>
<tr>
<td>R_coil_out</td>
<td>2.5[mm]</td>
<td>0.0025 m</td>
<td>Geometric parameters: the outside diameter of coil</td>
</tr>
<tr>
<td>I_current_Amp</td>
<td>20[A]</td>
<td>20 A</td>
<td>Operating parameters: coil current</td>
</tr>
<tr>
<td>N_coil</td>
<td>100</td>
<td>100</td>
<td>Coil parameters: coil turns</td>
</tr>
<tr>
<td>d_wire_coil</td>
<td>0.2[mm]</td>
<td>2E-4 m</td>
<td>Coil parameters: the diameter of the copper wire</td>
</tr>
<tr>
<td>L_coil</td>
<td>10[mm]</td>
<td>0.01 m</td>
<td>Geometric parameters: the length of coil</td>
</tr>
<tr>
<td>Pulse_Period_p</td>
<td>0.4[ms]</td>
<td>4E-4 s</td>
<td>Condition parameters: positive magnetization pulse period</td>
</tr>
<tr>
<td>P_rise</td>
<td>0.01[ms]</td>
<td>1E-5 s</td>
<td>Condition parameters: magnetization pulse rise / fall edge width</td>
</tr>
<tr>
<td>solver_step</td>
<td>P_rise*0.05</td>
<td>5E-7 s</td>
<td>Solver parameters: time of step</td>
</tr>
<tr>
<td>Pulse_Period_n</td>
<td>0.4[ms]</td>
<td>4E-4 s</td>
<td>Condition parameters: negative magnetization pulse time</td>
</tr>
<tr>
<td>Pulse_hold</td>
<td>0.4[ms]</td>
<td>4E-4 s</td>
<td>Condition parameters: positive and negative pulse hold time</td>
</tr>
<tr>
<td>F_sin</td>
<td>2[Hz]</td>
<td>2 Hz</td>
<td>Condition parameters: sinusoidal demagnetization period</td>
</tr>
<tr>
<td>Br</td>
<td>0.3[T]</td>
<td>0.3 T</td>
<td>Material parameters: initial residual magnetic flux density</td>
</tr>
<tr>
<td>Mr_z</td>
<td>Br/mu0_const</td>
<td>2.3873E5 A/m</td>
<td>Material parameters: initial residual magnetization</td>
</tr>
<tr>
<td>Bs</td>
<td>2[T]</td>
<td>2 T</td>
<td>Material parameters: saturated magnetic flux density</td>
</tr>
<tr>
<td>Ms_z</td>
<td>Bs/mu0_const</td>
<td>1.5915E6 A/m</td>
<td>Material parameters: saturation magnetization</td>
</tr>
</tbody>
</table>
IV.4.3. Mesh

The accuracy of the calculation and the speed of the computation are directly related to the discrete model / mesh (finite element representation). The more detailed the representation, the more accurate the calculation, but also the greater the computing time. Therefore, it is important to combine the different factors and rationally carry out finite element meshing.

COMSOL Multiphysics provides two ways for meshing: Free meshing and Mapped meshing. The Free meshing uses tetrahedron, quadrilateral or triangles to mesh, and changes the mesh quality by side length curvature and grid number. It is usually used for spatial free surface and complex entities meshing. The Mapped meshing uses the parameters such as the number of grids and the length of the cells to strictly control the mesh quality.

In our model, the Alnico5 and copper coil are meshed by Mapped (see Figure IV-4), and the remaining air is made with Free triangular. The specific element size parameters are shown table IV-2. The global meshed model is shown in Figure IV-5.

Figure IV-4 Mapped mesh of Alnico5 and copper coil
Table IV-2 Mesh data

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum element quality</td>
<td>0.1359</td>
</tr>
<tr>
<td>Average element quality</td>
<td>0.8917</td>
</tr>
<tr>
<td>Triangular elements</td>
<td>1864</td>
</tr>
<tr>
<td>Quadrilateral elements</td>
<td>200</td>
</tr>
<tr>
<td>Edge elements</td>
<td>260</td>
</tr>
<tr>
<td>Vertex elements</td>
<td>14</td>
</tr>
</tbody>
</table>

**IV.4.4. Study and model calibration**

To simulate the process of Alnico5 magnetization and reverse magnetization, we have to adjust the five parameters of Jiles-Atherton theory in the formula (4.3) - (4.7) so that the hysteresis loop is similar to the real one tested in [12]. So, parameter calibration is the first step. In the real tests of the hysteresis loop, the excitation is a sinusoidal function. Thus, we use the same type of signal for model calibration.

Figure IV-6 shows the hysteresis loop resulting from the COMSOL simulation. Figure IV-7 displays the internal average magnetic field $B_z$ (unit is Tesla, in the z-direction) and the coil current intensity $I$ (unit is 10 Amperes) in function of the time given in seconds. It is obvious that there is a phase lag
between current and $B_z$, this is the magnetic hysteresis. If we take a look at the two figures, then it can be observed that at $t = 0$ s the Alnico5 material begins to be magnetized and reaches the maximum near 0.1 s; then magnetization begins to decrease, and reverses near 0.28 s; near 0.36 s, it reaches the maximum in the reverse direction; when $t = 0.52$ s, it becomes zero again. This is the first hysteresis phase, and the process repeats again. It should be noted that from then on, the Alnico5 is no longer without magnetization. Thus, the hysteresis loop cannot coincide with the first period. In the hysteresis loop, when $H$ increases from zero to its maximum value and then decreases to zero, some residual magnetism remains (see point a), at this point the value of the magnetic flux density is also known as the remanent flux density.

The Hysteresis loops in Figure IV-6 do not coincide, which is because we use the Jiles-Atherton theory. In this theory, each step of the magnetization process is related to the previous step, and numerical simulation results depends on magnetization history. When the period is long enough, it will eventually stabilize.

![Hysteresis Loop](image)

Figure IV-6 Calibrated hysteresis loop by COMSOL
Figure IV-7 Relationship of the coil current intensity $I$ (unit is 10 A) and internal average magnetic field $B_z$ in function of the time (s).

Figure IV-8 shows the 3D magnetic flux density view. Figure IV-9 displays four important phases of the magnetization process. Figure IV-9 (a) shows the magnetic flux density when it reaches the maximum value. Figure IV-9 (b) shows the directions of the magnetic field when it starts to reverse. At this moment, it is obvious that the directions of the magnetic field in Alnico5 and outside are opposite. The interaction of the magnetic fields of the Alnico5 and the coil also causes the nearby magnetic field to become disordered. In Figure IV-9 (c), the Alnico5 is demagnetized. In Figure IV-9 (d), the magnetic flux density reaches the maximum value in the opposite direction.

Figure IV-8 3D magnetic flux density view
We use a pulse signal to change the magnetic field of SEP magnet. The pulse signal consists of a positive pulse followed by a negative pulse. To the best of our knowledge, COMSOL Multiphysics does not provide such a signal. Referring to Table IV-1, we first define two positive pulse signals \textit{rect1} (see Table IV-3 and Figure IV-10) and \textit{rect2} (see Table IV-4 and Figure IV-11).

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower limit</td>
<td>( P_{\text{rise}} )</td>
</tr>
<tr>
<td>Upper limit</td>
<td>( \text{Pulse_Period_p} + P_{\text{rise}}*2 )</td>
</tr>
</tbody>
</table>
Table IV-4 Definition of positive pulse signal: *rect2*

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower limit</td>
<td>Pulse_Period_p + Pulse_hold + P_rise*4</td>
</tr>
<tr>
<td>Upper limit</td>
<td>Pulse_Period_p + Pulse_hold + P_rise<em>4 + Pulse_Period_n + P_rise</em>2</td>
</tr>
</tbody>
</table>

Finally, we combine the two signals to obtain the complete pulse signal pw1 (see Table IV-5 and Figure IV-12).
We consider now the case where the excitation signal is a pulse. Pulse peak is 20 $A$. We get the new B-H curve, which is shown in Figure IV-13; where the internal average magnetic field $B_z$ is in Tesla. The coil current intensity $I$ (unit is 10 Amperes) is shown in Figure IV-14. Compare the point a in Figure IV-13 and Figure IV-6, the value in Figure IV-13 (0.8 T) is less than the one in Figure IV-6 (0.9 T); this is due to the non-linearity of the pulse signal, and the effect of non-linear inductance elements. When generating a magnetic field, eddy currents (Foucault currents) are also generated in Alnico5. These eddy currents, in turn, generates the anti-magnetic field, which will hinder the magnetization process, and prevents the Alnico5 from being completely saturated. This anti-magnetic field is enhancing radially from outside to the inside of Alnico5. Non-uniform magnetization often occurs when magnetizing the permanent magnet with a large cross-section, since the magnet surface is in the saturation state, but the middle portion is not. Figure IV-15 details the anti-magnetic fields in Alnico5 with COMSOL. The magnetizing current pulse width is short; pulse rise time is much shorter. When the pulse current increases, the anti-magnetic field becomes more apparent. Therefore, when designing SEP magnet, the diameter of Alnico5 cannot be too big.
Figure IV-13 B-H curve of the pulse signal

Figure IV-14 Relationship between internal average magnetic field $B_z$ and the coil current intensity $I$ (pulse case, unit is 10A)
By comparing Figure IV-6 and Figure IV-13, we can see that the sinusoidal signal is more favourable to achieve greater magnetic flux density than the pulse signal. Nevertheless, its frequency is too low for practical use in a modular robot where modules have to move rapidly. Thus, when a module needs to move quickly, we use pulses; and when it reaches a specified position, we use a sinusoidal signal in order to make the connection between the modules more efficient. This conclusion is very important, and we provide the sequel guidance for programming and control strategies.

IV.5. Simulation Results

We concentrate now on several points in relationship with the design of the SEP magnet. In the sequel, we detail the effect of coil turns, pulse intensity, the coverage area of the coil on the global behaviour of the SEP magnet.

IV.5.1. Effect of the number of coil turns

To analyze the effect of the number of coil turns, we make tests with up to 500 coil turns and measure the magnetic flux density. Figure IV-16 shows the trends of the magnetic flux density of Alnico5 center, $B_{\text{center}}$. In the beginning, $B_{\text{center}}$ increases with the number of coil turns. The growth rate is significantly reduced at 200 turns; $B_{\text{center}}$ reaches a maximum value at 300 turns, and does not increase anymore. As a conclusion, it is better to choose the number of coil turns between 200 to 300.
IV.5.2. Effect of the pulse intensity

We analyze now the effect of the intensity of the pulse, and consider peaks from 1 A to 30 A. Figure IV-17 shows the trends of the magnetic flux density $B_{\text{center}}$ of Alnico5 center, and the average magnetic flux density $B_{\text{average}}$. We observe that the greater the intensity of the pulse, the greater the magnetic flux density. We note that when the intensity is below 5 A, the hysteresis curve is distorted. At 20 - 30 A, although the pulse peak is large a few energy is required since the pulse is very short, and it will not cause damage to the circuit. Thus, it is better to choose a current intensity that is sufficiently large but that avoids the destruction of the circuits and equipment.
IV.5.3. Effect of the coverage area of coil

For a fixed number of coil turns and fixed current intensity, we consider now three configurations in the simulation:

a) Alnico 5 is half wrapped (see Figure 18 (a));

b) Alnico 5 is exactly wrapped (see Figure 18 (b));

c) Alnico 5 is extra wrapped (see Figure 18 (c)).

These three configurations correspond to tight, loose and very loose wrapping, respectively. Figure IV-20 displays the distribution of the magnetic flux density according to the coverage area. In Figure IV-18 (a), it can be seen that, if the Alnico5 is not fully covered, then the two ends (in the circle) cannot be magnetized. In Figure IV-18 (b) and Figure IV-18 (c), we observe that the Alnico5 can be totally magnetized, there are no significant differences, but the larger the coverage area, the smaller the magnetic flux density of Alnico5 center. This is because, when the coverage area increases, the magnetic flux density which is distributed to Alnico5 center becomes smaller. Thus, when manufacturing SEP magnet, it is better to exactly wrap Alnico5 with copper coil.

![Figure IV-18 Effect of the coverage area of coil. (a) half wrapped. (b) exactly wrapped. (c) extra wrapped.](image)
IV.5.4. Effect of the diameter of copper wire

We analyze now the effect of the diameter of copper wire which is used for making the coil. Figure IV-19 shows the trends of the magnetic flux density $B_{\text{center}}$ of Alnico5 center. We can notice that there is no significant difference when changing the diameter of copper wire between 0.01 mm and 0.2 mm. So, when choosing the copper wire, we only need to consider the maximum current it can withstand according to the American Wire Gauge (AWG), which is also known as the Brown & Sharpe wire gauge. AWG is a standardized wire gauge system used since 1857 predominantly in North America for the diameters of round, solid, nonferrous, electrically conducting wire.

Table IV-6 shows some standard wires in AWG. We take a close look at the fusing current; it is easy to see that the wire can withstand bigger current when the time is shorter. In our case, the pulse period is much shorter than 32 ms. Besides, in order to reduce the size of the SEP magnet, the smaller the diameter of the copper wire, the better. So, we choose the wire with the diameter between 0.127 mm and 0.202 mm.
### IV.6. Conclusion

This chapter first introduces the Magnetic hysteresis and the Jiles-Atherton model. Then based on the former theories we build a model in COMSOL Multiphysics. Finally, we have performed a series of numerical simulations to study the effect of different parameters like the number of coil turns or wrapping area. The simulation results play a guidance role in validating the design of SEP magnet. Some important conclusions can be given:

1) It is better to choose the number of coil turns between 200 and 300.

<table>
<thead>
<tr>
<th>AWG</th>
<th>Diameter (mm)</th>
<th>Diameter (per cm)</th>
<th>Area (mm²)</th>
<th>Resistance/length (mΩ/m)</th>
<th>1s (A)</th>
<th>32ms (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>0.405</td>
<td>24.7</td>
<td>0.129</td>
<td>133.9</td>
<td>39</td>
<td>218</td>
</tr>
<tr>
<td>27</td>
<td>0.361</td>
<td>27.7</td>
<td>0.102</td>
<td>168.9</td>
<td>31</td>
<td>174</td>
</tr>
<tr>
<td>28</td>
<td>0.321</td>
<td>31.1</td>
<td>0.081</td>
<td>212.9</td>
<td>24</td>
<td>137</td>
</tr>
<tr>
<td>29</td>
<td>0.286</td>
<td>35.0</td>
<td>0.0642</td>
<td>268.5</td>
<td>20</td>
<td>110</td>
</tr>
<tr>
<td>30</td>
<td>0.255</td>
<td>39.3</td>
<td>0.0509</td>
<td>338.6</td>
<td>15</td>
<td>86</td>
</tr>
<tr>
<td>31</td>
<td>0.227</td>
<td>44.1</td>
<td>0.0404</td>
<td>426.9</td>
<td>12</td>
<td>69</td>
</tr>
<tr>
<td>32</td>
<td>0.202</td>
<td>49.5</td>
<td>0.0320</td>
<td>538.3</td>
<td>10</td>
<td>54</td>
</tr>
<tr>
<td>33</td>
<td>0.180</td>
<td>55.6</td>
<td>0.0254</td>
<td>678.8</td>
<td>7.7</td>
<td>43</td>
</tr>
<tr>
<td>34</td>
<td>0.160</td>
<td>62.4</td>
<td>0.0201</td>
<td>856.0</td>
<td>6.1</td>
<td>34</td>
</tr>
<tr>
<td>35</td>
<td>0.143</td>
<td>70.1</td>
<td>0.0160</td>
<td>1079</td>
<td>4.8</td>
<td>27</td>
</tr>
<tr>
<td>36</td>
<td>0.127</td>
<td>78.7</td>
<td>0.0127</td>
<td>1361</td>
<td>3.9</td>
<td>22</td>
</tr>
<tr>
<td>37</td>
<td>0.113</td>
<td>88.4</td>
<td>0.01</td>
<td>1716</td>
<td>3.1</td>
<td>17</td>
</tr>
<tr>
<td>38</td>
<td>0.101</td>
<td>99.3</td>
<td>0.00797</td>
<td>2164</td>
<td>2.4</td>
<td>14</td>
</tr>
</tbody>
</table>

Table IV-6 AWG wire sizes
2) The greater the intensity of the pulse, the greater the magnetic flux density. It is better to choose an intensity that is big enough but also avoids the destruction of the circuits and equipment.

3) When manufacturing SEP magnet, it is better to wrap Alnico5 with copper coil exactly.

4) There is no significant difference when changing the diameter of copper wire between 0.01 mm and 0.2 mm. Considering the voltage and current, it is better to choose the wire with the diameter between 0.127mm and 0.202mm.

We also need to note that, the numbers of the coil turns, the diameter of the copper wire, the thickness of coil and the coverage area of the coil are interrelated, and their relationship can be calculated.

References in Chapter IV


Chapter V. Hardware Design: Circuit and Structure

V.1. Introduction

The design of SEP magnet and the linear motor made of SEP magnets build the foundation of our distributed modular robot system. This Chapter is mainly a presentation of the design and hardware of our distributed modular robot system, whose name is DILI.

The DILI modular robot was designed after the Smart Block project as seen in the previous chapters. In this chapter, we present our contributions regarding, in particular, the design of an electronic circuit which allows us to achieve fast and smooth module motion. We also detail the design of the DILI module. As already mentioned in Chapter III, SEP magnets move thanks to current pulses. Each DILI module will contain several linear motors. We recall that each linear motor needs at least two SEP magnets. As a consequence, the control system and control strategy are complex. In Section V.2, we consider the design of the electronic circuit dedicated to pulse generation (our goal is to obtain a simple and small system, with high execution speed). Section V.3 introduces the microcontroller and circuit board.

The structure of the modular robot is very important, as described in Chapter II. There is a variety of modular robot structures. The structure directly determines the motion possibilities. At the same time, a reasonable structure can also ensure energy savings during the process of moving. We also note that, in the case of 2D motion, the robotic module needs to have the function of connection and motion. In Section V.4, we concentrate on the physical implementation of the DILI robot.

Section V.5 presents the motion and connection principle or DILI robot. In Section V.6, we test the performance of the DILI robot via a series of experiments, such as the speed on different surfaces, holding force. We test its vertical force, which also laid the foundation for DILI to achieve 3D movement in the future. The conclusion of this chapter is given in section V.7.
V.2. Pulse Signal Generation Circuit

As mentioned in chapter III, pulse signals are used to change the direction of magnetic field of SEP magnets. Coercive force (intrinsic) is the property of the material that decides what magnetic field strength is needed for magnetization. Axial and diametrical magnetization can be made in standard inductors, i.e. solenoids. However, radial, multiple poles, or any other complex kind of magnetization must be obtained thanks to a special magnetization device.

When the pulse signal passes through the solenoid, it generates a pulse magnetic field in its interior. In general, when the peak value of the pulse magnetic field reaches 3-5 times the material coercivity, the material can be fully magnetized [1].

V.2.1. Capacitance pulse discharge

There are two main methods for generating large pulse current, using a strong pulse power or using a capacitor [2]. Since distributed robot systems generally require a smaller volume, we choose the latter one. Capacitance pulse discharge also has the advantage of a simple structure; it requires low power and is easy to control. Figure V-1 displays a schematic diagram of it.

![Schematic diagram of capacitance pulse discharge](image)

As shown in Figure V-1, when the switch $K1$ is closed, capacitor $C$ will be charged by the power source. Then disconnect $K1$, close $K2$; the circuit forms a typical RLC oscillator circuit. In this case, a constant coefficient second order linear homogeneous differential equation can be formed; $u$ is as an unknown quantity. That is given as follows,
\[ \frac{LC}{dt^2} \frac{d^2 u_c}{dt^2} + RC \frac{du_c}{dt} + u_c = 0, \]  

(5.1)

Let \( \beta \) be the damping coefficient, \( \beta = \frac{R}{2\sqrt{\frac{L}{C}}} \), and \( \omega \) to be the angular frequency \( \omega = \sqrt{\frac{1}{LC}} \), \( i = -C \frac{du_c}{dt} \).

The initial conditions are when \( t = 0^+ \), \( u_c = U_0 \), \( i = 0 \). Depending on different circuit parameters, the following three conditions are calculated:

1) When \( \beta = 1, R = 2\sqrt{\frac{L}{C}} \), the circuit is in critically damped state,

\[ \frac{LC}{dt^2} \frac{d^2 u_c}{dt^2} + RC \frac{du_c}{dt} + u_c = 0, \]  

(5.2)

2) When \( \beta > 1, R > 2\sqrt{\frac{L}{C}} \), the circuit is in over-damped state,

\[ i(t) = \frac{CU_0\omega}{\sqrt{\beta^2 - 1}} e^{-\beta\omega t} \left( w\sqrt{\beta^2 - 1}t \right), \]  

(5.3)

3) When \( 0 < \beta < 1, R < 2\sqrt{\frac{L}{C}} \), the circuit is in under-damped ringing state,

\[ i(t) = \frac{CU_0\omega}{\sqrt{1 - \beta^2}} e^{-\beta\omega t} \sin \left( w\sqrt{1 - \beta^2}t \right) \]  

(5.4)

Waveforms of the signal associated with three different states are shown in Figure V-2. Intuitive looking, the current peak in the case of the second state is too low. In the third case we have a high-current peak, but the presence of a negative pulse will play the role of degaussing. So, the case of first state is suitable for magnetization.
V.2.2. H-bridges for controlling the magnetization direction

In Figure V-1, we can observe that the width of the pulse is determined by the time to turn-on and turn-off the switch K2. Since we want to control the SEP magnet to achieve both positive and negative direction of the magnetization, we must use a special switch to obtain two-way current control; this special switch is H-bridge. H bridge is an electronic circuit that enables a voltage to be applied across a load in either direction. This circuit is often used in robotics and other applications to allow DC motors to run forward or backward [3].

An H bridge is built with four switches (electronical or mechanical). By controlling the four switches, we can control the load to move forward, move backward and stop. Figure V-3 shows its topology, and its working principle, the load is a motor. When the switches S 1, S 4 are closed, and S 2, S 3 are opened, a voltage is applied across the motor from left to right. When the switches S 1, S 4 are opened, and S 2, S 3 switches are closed, the voltage is applied across the motor from right to left. Table V-1 details the status of switches in H-bridge and its result. If only one switch is closed, H-bridge cannot work. Thus, these states are not included in the table.
H-bridge topology

H-bridge forward the motor

H-bridge reverse the motor

Figure V-3 Principle of H-bridge

Table V-1 Status of switches of H-bridge

<table>
<thead>
<tr>
<th>Motor status</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor moves right</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Motor moves left</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Motor brakes</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Short circuit</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
V.2.3. Dead-time in H-bridges

MOSFET [3] technology responds quickly and can pass high current; it is used as a switch of H-bridge for robots. Figure V-4 is a typical scheme of H-bridge made from MOSFET. In a practical case, we found that such a circuit has a dead-time phenomenon. Dead-time is also called as shoot-through protection or no-overlap PWM (Pulse Width Modulation). Generally speaking, its presence is a good thing in most instances.

When turning one MOSFET off, while turning the other MOSFET on, for a short while both the low and high-side MOSFETs are potentially conducting to a certain degree, creating a relatively low resistance path from the supply to the ground. This can result in a current spike which is quite problematic. The dead-time permits one to avoid this problem.

![Figure V-4 Scheme of H-bridge circuit](image)

Dead-time is an inherent characteristic of MOSFET. It is mainly due to a small amount capacitance in MOSFET. This capacitance information is usually found in the MOSFET data sheet. Table V-2 displays the capacitance parameters of two common transistors.
### Table V-2 Capacitance parameters of two MOSFET

<table>
<thead>
<tr>
<th>Items</th>
<th>MOSFET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Irf8736pbf</td>
</tr>
<tr>
<td>Input Capacitance</td>
<td>2315 pF</td>
</tr>
<tr>
<td>Output Capacitance</td>
<td>449 pF</td>
</tr>
<tr>
<td>Reverse Transfer Capacitance</td>
<td>219 pF</td>
</tr>
</tbody>
</table>

**V.2.4. Drawbacks of dead-time**

The presence of dead-time can be a drawback of SEP magnet. A MOSFET is limited in its speed to switch on and off by the amount of time that it takes to charge and discharge the small amount capacitance in its structure. The most direct consequence of dead-time is to cause a delay. Theoretically, the dead-time can be calculated. The most important parameters are turn-on and turn-off times.

In addition to the delay, there are other effects of dead-time. In Figure V-4, we suppose that in the beginning, during the dead-time, Q1 is open, Q2, Q3, and Q4 are off. Since the current flows in different directions, the power unit output level will be different. As shown in Figure V-5, when the current flowing through the power unit is greater than 0, that is \( i > 0 \), the power unit output voltage is \( U_{dc} \), conversely when \( i < 0 \), the output level is 0. Therefore, during the dead-time, since the current flows to a different direction, the actual output voltage of the power unit is as shown in Figure V-5 (e) and (f).

Obviously, when \( i > 0 \), the actual output voltage will increase by amount that corresponds to \( \frac{U_d T_d}{T_s} \), when \( i < 0 \), the actual output voltage will decrease by amount that corresponds to \( \frac{U_d T_d}{T_s} \). This will cause the distortion of the output waveform; generate new harmonic components; reduce the effect of active filtering.
V.2.5. Dead-time controllable H-bridge

We measured the dead-time with an oscilloscope. It is equal to 130ms. This is longer than charging time of the capacitor (100ms). So, we improved the H-bridge whose dead-time is controllable; the improved circuit is presented in Figure V-6. In this new circuit, each MOSFET can be controlled independently by one Input / Output (I/O) of micro-controller, instead of one I/O to control a half-bridge like in [4]. The advantage is that the ON and OFF time of each MOSFET can be precisely calculated and can be directly controlled by the microcontroller. Meanwhile, the dead-time can be controlled according to the expected speed of modules.

In addition to re-improving the H-bridge, we also used a half-bridge multiplex design. With this design, the complexity of the circuit can be reduced. Thereby, the size and weight of actuator can also be reduced. This is necessary for micro-robots. The specific structure is as shown in Figure V-7, the switches S 1 and S 2 form a common semi-H-bridge, like switches S 3 and S 4 or S 5 and S 6 or S 7 and S 8, respectively. Thus, the common semi-H-bridge and the other three semi-H-bridges form a total of two pairs of H-bridges, with a total of four semi-H-bridges instead of six. For example, when the magnetization direction of SEP 2 need to be controlled in positive, we only need to close switch S 1 and switch S 6, the other remains open. We note that this design cannot simultaneously magnetize two SEP magnets since we could obtain incomplete magnetization.
Figure V-6 Dead-time controllable semi-H-bridge

Figure V-7 Half-bridge multiplex design
V.3. Microcontroller and Circuit

DILI robot system uses the STM32F103, a 32-bit enhanced flash memory microcontroller as the core. STM32F103ZE is based on Cortex-M3, which is specifically designed to meet the requirements of embedded systems that must meet high performance, low power, and real-time applications. The maximum operating frequency of this core is up to 72 MHz. Its rich interface resources greatly simplify the system hardware, while greatly reducing system power consumption. This also lays the foundation for the future functional upgrading of the system. Table V-3 presents the key features of STM32F103. The circuit that we designed is shown in Figure V-8, it is a 35mm*35mm board. The PCB (Printed Circuit Board) and real circuit board are shown in Figure V-9. In order to facilitate the scalability of this system, we designed another board which contains only 8 semi-H-bridges, it has the same size as the main circuit and can connect to the main board. Figure V-10 shows the detail of the bridge circuit board.

<table>
<thead>
<tr>
<th>Key features</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low power consumption</td>
<td>Three low power modes: Hatch, Stop and Standby.</td>
</tr>
<tr>
<td>Debug mode</td>
<td>Support for serial debug (SWD) and JTAG interface download.</td>
</tr>
<tr>
<td>Memory</td>
<td>With built-in high-speed memory (512K Flash and 64K SRAM), it does not need to use a special external Flash or ROM.</td>
</tr>
<tr>
<td>I/O port</td>
<td>26/36/51/80 compatible 5V multi-function bi-directional I/O port, all I/O port can be mapped to the external 16 interrupts.</td>
</tr>
<tr>
<td>Timer</td>
<td>It has up to 11 timers: four 16-bit timers, two 16-bit 6-channel advanced control timers, two watchdog timers (an independent watchdog and window watchdog), Systick timer and two 16-bit basic timers for driving the DAC.</td>
</tr>
<tr>
<td>communication interfaces</td>
<td>It also has up to 13 communication interfaces: two IIC interface (SMBus/PMBus), five USART interface, three SPI interfaces (18Mbit/s), one CAN interface (2.0B), one USB2.0 full-speed interface and one SDIO interface.</td>
</tr>
<tr>
<td>Two 12-bit AD/C converters</td>
<td>16 input channels, conversion time, is 1 microsecond (measuring range 0-3.6V), with dual sampling, hold function.</td>
</tr>
</tbody>
</table>
Figure V-8 Circuit of the main board

Figure V-9 PCB and the real main board for controlling our robot
For controlling propose, we connect a Bluetooth module to the main board the serial port. Thus, we can send information to the main board by smartphone or PC.

**V.4. Structure of DILI Robot**

This subsection is devoted to the presentation of the DILI module. As shown in Figure V-11, we design DILI according to a cubic shape with sides 1.5 cm. The basic structure is built in one part via 3D print technology with the material of PLA (Poly Lactic Acid). In addition to the top and bottom, each module has four work surfaces devoted to both motion and connection. The bottom is smooth and used for sliding. Each module has six large holes for SEP magnets and four small holes for NdFeB magnets; they are placed in two layers. The only strict limit of the distance between the NdFeB magnets is half bigger than the distance between the EP magnets so that cubes can move in the desired direction. The Alnico5 magnet in SEP magnet has a size of 1.5 mm in diameter and 8 mm in length and wrapped with 250 turns of 0.15 mm enamel copper wire.
Figure V-11 Structure of DILI robot

Figure V-12 and Figure V-13 are section views of large holes and small holes on DILI module. The diameter of the large holes are 4 mm, they penetrate from the outer wall to the inner; the four holes that are close to the wall are embedded inside the wall. This kind of design can not only save space but also can reduce the weight. We expect also this design to improve the stability of the module and lead to smooth motion. The diameter of the holes are 2 mm, in order to install NdFeB magnets precisely and keep them parallel to the outer wall, the small holes are not situated in the wall. Figure V-14 shows the 4 working surfaces (a), 6 SEP magnets (b) and 4 NdFeB magnets (c) with real DILI module. We place the small holes and big holes sufficiently apart so that the magnetic field generated by SEP magnet does not affect the NdFeB magnets which could have an impact on the motion of modules and the strength of connections between modules.
Figure V-12 Details of big holes on DILI for SEP magnets, right part corresponds to a cut of DILI module

Figure V-13 Details of small holes on DILI for NdFeB magnets, right part corresponds to a cut of DILI module
In DILI, the working surfaces between modules are divided into two layers according to the height. The surface with NdFeB magnets faces the surface with SEP magnets in the same height, as shown in Figure V-15. The three SEP magnets and two NdFeB magnets form a linear motor. Thus, each module can move by itself or can be driven by other modules. Placing the SEP magnets and NdFeB magnets in two layers can not only guarantee every side has the ability of motion, but also makes full use of the space and reduces the volume.
Figure V-15 Relative positions of two DILI modules for working purpose

V.5. Motion and Connection Principle of DILI Robot

Figure V-16 shows the status of SEP magnets in a complete movement process along a distance of one module (from left to right). Six steps are needed to achieve the whole motion. At each step, only one SEP magnet changes its status and the system only needs energy at that time. The order of the SEP magnets which change the status is 3-1-2-3-1-2. When the movement ends, modules do not need the energy to fasten to each other, since modules can fasten each other by the permanent magnetic field generated by Alnico5 magnets and NdFeB magnets. The new linear motor can be made as tiny as possible; the limitation is the size of Alnico5 magnet and coil. The new linear motor is easy to build and can provide both driving force and fastening force. Another advantage of the linear motor is that it can move in any direction, due to the controllability of the polarity of Alnico5 magnet. For example, if we want to return the module to the original location, we only need to change the status of SEP magnets in order 1-3-2-1-3-2.
V.6. Experiments

We concentrate on the motion and connection functions. We have built a platform to test the two functions. For the speed, we have designed an ultrasonic velocity tester, by detecting the send and return signal to determine the speed of modules. We use a miniature tensile force measure instrument to measure the holding force.
V.6.1. Speed test

Table V-4 shows the speed of DILI on different surfaces for three operating modes. These three modes are:

- the stable mode;
- the enhanced mode;
- the fastest mode.

In the stable mode, the DILI module can move without error. The parameters of stable mode are chosen after many experiments; this mode can not only guarantee fast motion but also ensures the stability of the system.

The enhanced mode is relatively similar to the stable mode; the difference is that a 0.8 A continuous current is applied to the coil (for more details we refer to subsection 2.3).

The fastest mode is achieved by reducing the dead-time to few microseconds. We also reduce the time between two consecutive pulses as much as possible. It should be noted that, in the fastest mode, the motion may present some error, like an incomplete motion. The reason is that the Alnico5 magnet is not fully magnetized in the fastest mode.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Mode</th>
<th>Glass</th>
<th>Paper</th>
<th>Wood</th>
<th>Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fastest mode</td>
<td>20mm/s</td>
<td>20mm/s</td>
<td>18mm/s</td>
<td>18mm/s</td>
</tr>
<tr>
<td></td>
<td>Stable mode</td>
<td>13mm/s</td>
<td>13mm/s</td>
<td>12mm/s</td>
<td>12mm/s</td>
</tr>
<tr>
<td></td>
<td>Enhanced mode</td>
<td>9mm/s</td>
<td>9mm/s</td>
<td>9mm/s</td>
<td>9mm/s</td>
</tr>
</tbody>
</table>

We sort the friction between the surfaces and the DILI from small to large: $V_{\text{glass}} < V_{\text{paper}} < V_{\text{wood}} < V_{\text{cement}}$. For each mode, we note that the speed is almost indistinguishable on the different surfaces.

The reason that the surface has slight effects on the speed is that the movement of DILI is controlled by pulses. The movement is stepping forward rather than linear. When the block moves from one position to the next position, the initial speed is zero; the final speed is also zero, there is no speed
accumulation. So, the previous move did not affect the next move. Figure V-17 is the screenshot of the test. A video of our test is presented in [5]. On the video, we observe a particularly smooth motion of the module; experiments were carried out on a wood surface with the Stable mode in Table1.

![Figure V-17 Speed test](image)

**V.6.2. Holding force test**

The holding force that we tested is the positive tension between two blocks. The holding force is related to the magnetic field of Alnico5 magnet in SEP magnet, holding force reaches the maximum when Alnico5 magnet reaches saturation. The intensity of the magnetic field of Alnico5 magnet is related to the number of pulses and the applied voltage. Figure V-18 shows the results of holding force test in millinewton at different voltage values and a different number of pulses. We can summarize the following results:

a) If the voltage is less than 4 V, the circuit cannot produce a holding force.

b) Holding force increases as the voltage rises.
c) Generally, the higher the number of pulses, the greater the holding force. But there is a saturation value, when the saturation value is reached, if the voltage does not change, then the holding force does not increase as the number of pulses increases.

d) The greater the voltage, the less the number of pulses required to reach a saturated holding force. For example, when the voltage is 16 V, only one pulse is needed to reach the saturated holding force.

We also note that the sinusoidal signal is more favourable than a pulse for the magnetization of the magnet to achieve greater magnetic flux density. So, we changed the pulse to sinusoidal signal and measured the holding force again. The result is displayed in Figure V-19. Obviously, with a sinusoidal signal, the holding force can be greatly increased. In some case, with the same voltage (i.e. 16 V), the holding force generated by the sinusoidal signal (140 mN) is nearly twice as much as the holding force generated by pulse signal (75 mN).

![Figure V-18 Holding force test with pulse signal](image-url)
V.6.3. Vertical force test

This version of DILI was designed for 2D motion. We test the vertical holding force as shown in Figure V-20. Since the size of SEP magnet is small, the holding force of the vertical surface is enough for holding but not enough for moving. When trying to move upward, there is a moment when module falls that corresponds to the smallest vertical holding force (static). In the next generation of DILI robot, we plan to improve the design for permitting modules to have 3D motion.
V.7. Conclusion

Based on the research work in Chapter III and Chapter IV, we successfully build the DILI, module of our distributed robot system. Firstly, in order to achieve a quick response, we have analyzed the dead-time in the circuit and designed two circuits, the main circuit, and the bridge circuit. Then we have designed the structure. The DILI module is a cube with 4 work surfaces, which can move in four directions. The principles of motion and connection are also detailed in this chapter. Finally, we have tested the performance of DILI robot through a series of experiments. We have sorted the friction between the surfaces and the DILI from small to large: glass < paper < wood < cement. For each mode, we note that the speed is almost indistinguishable on the different surfaces. About the holding force, we can summarize the following rules:

a) If the voltage is less than 4 V, the circuit cannot produce a holding force.

b) Holding force increases as the voltage rises.

c) Generally, the more the number of pulses, the greater the holding force. Nevertheless, there is a saturation state whereby the holding force does not increase when the number of pulses increases.

d) The greater the voltage, the less the number of pulses required to reach a saturated holding force. For example, when the voltage is 16V, only one pulse is needed to reach the holding force at saturation state.

References in Chapter V


Chapter VI. Distributed Algorithms and Simulation Software for DILI Robot System

VI.1. Introduction

Modular self-reconfigurable robotic systems are usually composed of tens or hundreds of modules. Their control is mainly divided into centralized control and distributed control. Both classes of methods have their own advantages and drawbacks. These classes of methods are suitable for different types of applications.

The structure of centralized control is shown in Figure VI-1 (a). Only one controller is used to control multiple robots. The advantage is that the topology of the control system is simple. But the centralized controller is a single node system. When the control system fails, it will likely cause instability or even paralysis of the global system. In addition, the controller needs to communicate with the modules and dynamically assign them tasks. When the number of modules increases, the traffic and computations in the controller increases rapidly, which puts forward higher requirements for the computation performance of the controller. Thus, this type of control methods is only applicable to small-scale modular robot systems. When the configuration changes, the control method needs to make a corresponding change. This approach is not scalable and difficult to adapt to complex environments.

The structure of distributed control is shown in Figure VI-1 (b). Distributed control methods do not have a hierarchical structure. Modules only carry out task planning according to the local information, which allows scalability and robustness. Modules cooperate with other modules to complete a given task. Obviously, this reduces the data traffic. Distributed control results in higher robustness and stability throughout the system. We note that a single module does not have the global information.
Obviously, distributed control is more suitable for DILI robot since it is designed with multiple modules. This chapter deals with distributed algorithms and the simulation of motion of DILI modules via a simulator that we have designed in order to test and validate distributed algorithms. Firstly, we discuss the capabilities of DILI modules which are presented in Section VI.2. Section VI.3 details the distributed algorithms. A simulator of distributed algorithms for DILI robot system is presented in Section VI.4. The conclusion of this chapter is given in Section VI.5.

VI.2. Capabilities of DILI Module

Chapter V has already presented the motion principle of DILI module. In this subsection, we concentrate on module motion. We begin by a definition of module motion that will be used in the remaining part of this chapter.

Definition: without loss of generality, a module motion will represent a move of one or several modules along the same direction on a distance of one module.

VI.2.1. Elementary motion

Module motion relies on the interactions between modules; that is, one module slides along another module. Furthermore, when a module moves, at least two surfaces / modules are needed. As shown in Figure VI-2 (a), if we want to move module 1 to the right, then we need surface 1 as current support, and surface 2 as future support.
These characteristics make the motion of DILI very simple as compared with other distributed robotic systems. Nevertheless, this leads to some limitations on the motion as well as difficulties to complete complex tasks and even blocking situations. Figure VI-2 (b) displays an example of a blocking situation where modules 1, 2, 3, and 4 do not have another surface as future support of the motion. As a consequence, all modules cannot really carry out a module motion. This kind of situation is common in the motion process of cube-shaped modular robot systems.

![Figure VI-2 Elementary motion of DILI module](image)

Also, we note that elementary motion of DILI module has no expansion capability. Figure VI-3 displays an example whereby, dotted arrows represent possible motion and direction. Module 1 can move one step to the east or module 3 can move one step to the north. After the motion of modules 1 or 3, some other modules can also move; but in any case, $W$ (width) and $L$ (length) will not change, that is, the change of shape can only happen in their own coverage area, they cannot expand the boundary. Without the possibility of expansion, the motion would be very limited.

![Figure VI-3 Elementary motion of DILI module without expansion capability](image)

**VI.2.2. Extended motion capabilities of DILI module**

We consider now several types of complex motion mechanisms that are also possible with DILI module, i.e., Push, Pull, and Carry. Figure VI-4 displays examples of extended capabilities of the DILI
robot system.

(a) Push, shows module 1 pushes module 2 from left to right;
(b) Pull, shows module 1 pulls module 2 from right to left;
(c) Carry, shows module 1 carries module 2 to right or left. Details of each capability will be given in the sequel.

VI.2.3. Push capability

Push capability permits a module to push another module (see Figure VI-4 a). In order to ensure that the pushed module does not affect the movement, the SEPs of that module can be demagnetized first.

Push capability is an important capability of DILI module because it can provide expansion capacity. Figure VI-5 (a) is a top view of four DILI modules, in a two-dimensional plane. Initially, the total width is $W$, and total length is $L$. Module 1 can push module 2 to the west, as shown in Figure VI-5 (b), the arrow represents one module motion, the total width of the set of modules becomes $W + I$, where $I$ is the length of a module. If we consider the push capability of module 4, then it can push module 2 to the north, as shown in Figure VI-5 (c), the total length of all modules becomes $L + I$. Therefore, the push function will permit one to obtain expansion.
Another feature of the push capability is to facilitate turning. DILI is a smart system with distributed intelligence, so the turning ability is particularly important. Figure VI-6 gives an example of a module that turns. As presented before, DILI module can slide along another module in two directions. But in the edge of a path, it cannot turn directly. In Figure VI-6, if we want to move module 1 from the initial position to position A, we need to seek the support of another module, i.e. module 2. Module 2 pushes module 1 to the edge; then module 1 has two sliding surfaces, then after one step, module 1 arrives at position A.

**Remark 1**, one can encompass easily turns to the left by using a similar principle.

**Remark 2**, the push function can also be assimilated to the motion of trains of blocks like in [1].
**VI.2.4. Pull capability**

The deformation of the modular robot is a complex process of expansions and contractions; in particular, the pull capability permits one to contract the modular robot.

With the pull capability, a module pulls another module (see Figure VI-4 b). As shown in Figure VI-7, module 1 pulls module 2 to the west, the total width of all modules changes from $W$ to $W - l$, where $l$ is the length of a module. Thus, the main function of pull capability is to provide a kind of contraction.

![Figure VI-7 Pull capability providing contraction](image)

It should be noted that when considering pull capabilities unless it is on the edge of the path, the module that is driven either can change the states of the internal SPE magnets to fit the movement or can be demagnetized.

**VI.2.5. Combined push and pull**

There is a special situation that we need to discuss here, which is shown in Figure VI-8. In this case, the module 1 and module 2 share one surface, the arrow shows the direction of motion. At this point, each module does not have a complete surface; the driving force of one module is not enough for pushing or pulling another module. So, a combination of push and pull is needed. Module 1 provides pull force, and module 2 provides push force. This is a cooperative process; we can control module 1 and module 2 as one module. We take a look at the state of the internal magnets in the related modules. There is an attractive force between NdFeB 1 and SEP 1, a repulsive force between NdFeB 1 and SEP 2; and repulsive between NdFeB 2 and SEP 3, SPE 4. The result of several force interactions is that module 1 and module 2 move to the right. It should be noted that the control of this situation is more
difficult than only push or pull.

VI.2.6. Carry capability

Carry capability corresponds to the case when a module carries another module (see Figure VI-4 c). The module which is carried does not need to have the motion ability. The existence of carry capability can effectively reduce the number of movements. This point will be presented in detail in subsection VI.4.

VI.2.7. Tests of DILI module

Whatever the push, pull or carry capabilities, the key to achieving these capabilities lies in the loading capacity of DILI module. Through experiments, we prove the feasibility and stability of these three capabilities. Figure VI-9 presents our experiments. Modules 1 to 4 support motion of module 5, module 5 provides a driving force, and module 6 is the module that is driven. The arrow shows the direction of motion. An experiment video is shown in [2].
VI.3. Distributed Algorithm

In this section, we present the distributed algorithm for controlling multiple connected DILI modules so that they form a specific shape via cooperation like for example a smart conveyor from a given origin to a destination (see Figure VI-10).

We also did tests about driving two modules. The experiments show that one module can push or pull two modules, but the motion is not as good as when driving only one module. When carrying two modules, since the torque is too large, the modules tend to separate from the support. Thus, we only consider the case of driving one module in the sequel.
**VI.3.1. Basic principle of the distributed algorithm**

A set of DILI modules is available on the surface; we assume that the modules are connected and that one module occupies the cell that corresponds to the beginning of the smart conveyor, i.e. the position of the input I. The end of the smart conveyor is also called the output and is denoted by O.

We propose a distributed iterative algorithm in order to set up a smart conveyor. The distributed iterative algorithm looks for a solution that gives the shortest path between input I and output O; at the same time, it tries to minimize the number of module motion. Our distributed algorithm is an exact method for the shortest path problem and a heuristic for the module motion problem.

The distributed algorithm contains 3 steps (see Figure VI-11).

Step 1: distributed election of a module that could be a good candidate for possible motions to the output O.

Step 2: definition of a square domain centered at the selected module and study of possible motions of modules in this domain.

Step 3: when there is no possible motion in the domain, then go to step 1.
VI.3.2. Details

Our algorithm is based on distributed iterative elections of modules that can be good candidates for possible motions to the output O. From time to time; a module is elected in an asynchronous distributed manner see Figure VI-11. We then define a square domain that is centered at the elected module. Modules within this square will be chosen for possible motion. We have considered implementations of our distributed algorithm with 3x3 or 5x5 squares; each cell within the square domain represents the possible position of a module.

For facility of presentation, we consider here the case when input I and output O are in the same column. We introduce a coordinate system with output as the origin, the line from output to input is the x-axis, the y-axis is perpendicular to the x-axis (see Figure VI-12), and we note that the direction of the y-axis does not affect the calculation done in the sequel.
We introduce now a cost function \( F \) that associates to each position of the cell on the surface a value related to its position relatively to the output O. When the module belongs to the column between input I and output O (x-axis), we assign a value equal to 100,000,000 in order to prevent that the module that occupies this position leaves the shortest path between I and O. The cost function is given as follows.

\[
F(x, y) = \begin{cases} 
100000000 & \text{module } \in \text{x-axis} \\
 x^4 + y^2 & \text{otherwise}
\end{cases}
\]

(6.1)

We then compute a value \( \delta \) which permits one to evaluate the possible gain of the modules when moving towards the output O.

\[
\delta = \sum_{\text{matrix} \in 3 \times 3}(F(x_i, y_i) - F(x_{i+1}, y_{i+1}))
\]

(6.2)

where \( i \) denotes the current position, and \( i + 1 \) represents the next step. Note that, the module elected via the distributed election algorithm corresponds to the module with maximum value.

**VI.3.3. Step 1: distributed election**

The procedure of distributed election is based on the distributed procedure of Dijkstra and Scholten [1] that use activity graph and acknowledgment of messages. All the modules store in their registers their position \((x, y)\) in the coordinate system. In the beginning, only the module situated at Input I, called the **Root** is active. The **Root** sends messages to its neighbor in order to activate them. We say that the **Root** is the **Father** of its neighbors. Each active module computes the value \( \delta \).

Each activation message activates a neighboring module that becomes a **Son**. Typically, activation messages are of the type:

\[
\text{Activate } [\text{Father, Son, } F(x,y), \ \delta, ID_\text{max}] \]

(6.3)

where the different fields of the message are: the ID of the sender (**Father**); the ID of the destination (**Son**), \( F(x,y), \ \delta \) and \( ID_\text{max} \), respectively.

As the computation progresses, the activity graph evolves, and more and more modules become
active. At some finite time, all modules have been activated and have computed $\delta$. Active modules that cannot activate neighbors anymore since they do not have a neighbor, but their father, or since all their neighbors have been activated by other modules become inactive and send an acknowledgment message to their father. Similarly, active modules that have received acknowledgements from all their sons become inactive and send an acknowledgment message to their father. Acknowledgment messages are of the type:

$$ Ack \{Son, Father, F(x,y), \delta, ID_{\max}\}, $$

where the different fields of the message are, the ID of the sender ($Son$), the ID of the destination ($Father$), $F(x,y)$, $\delta$ and $ID_{\max}$, respectively.

In the end, only the Root is active. This ends the first phase of the election algorithm. The Father then elects the module with $\delta_{\max}$. If there are several modules with the same $\delta_{\max}$, then the Root elects randomly one module with $\delta_{\max}$ and sends a Select message to the elected module. The selection message is routed to the elected module according to the Father/Son path obtained in the first phase of the election algorithm. The Elected module sends an acknowledgement message to the Root. Upon reception of the acknowledgement message, the Root becomes inactive. The distributed election is then terminated.

**VI.3.4. Step 2: definition of square domain centered at the selected module**

We define a square domain centered at the module elected at step 1 and consider possible motions of modules within this domain. This domain can be a 3x3 or a 5x5 domain. We can also choose a combination of 3x3 and 5x5 domains. In the cases of 5x5 domain and combination of 3x3 and 5x5 domains, the distributed algorithm will try to carry out at most 20 module motions in the 5x5 area. We emphasize that computations take time when considering large domains like 5x5 domain. In the case of a combination of 3x3 and 5x5 domain, the distributed algorithm works first on the 5x5 domain. If no module motion is possible, then the distributed algorithm concentrates only on a 3x3 domain. Details on this strategy will be presented in the sequel of this subsection.

We consider module motions allowed by the physical system. The area occupied by a module can
be seen as a cell. In order to check if a module can move, we examine the initial state of the cell as well as the state of neighbouring cells, i.e., if their positions are initially occupied by modules or not. The approach we consider here is slightly different from the one in [1].

We introduce a local square matrix, i.e., the Presence Matrix. The Presence Matrix shows the corresponding state of a cell and the state of adjacent cells. The entries of the Presence Matrix are equal to 1 if the cell is occupied by a module and equal to 0 if that position is not occupied by a module. For facility of presentation, we consider here only 3x3 matrix.

We display now an example (see Figure VI-13).

![Presence Matrix](image)

Figure VI-13 Position of modules (in gray) and associated Presence Matrix

We consider the associated 3x3 Presence Matrix $M_p$.

$$M_p = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \quad (6.5)$$

In step 2, the distributed algorithm computes all possible module motions toward the output O in the considered 3x3 area. More precisely, the distributed algorithm determines what motion can be carried out by the different modules contained in the 3x3 domain. The different modules are considered in sequence. A module motion is carried out if and only if there is support of other modules, i.e. if there is one or several adjacent entries equal to 1 in the 3x3 Presence Matrix, the future position is empty (corresponding entry of the future position in the Presence Matrix is equal to 0) and no module is left alone.
As an example, the module whose position corresponds to the third line and third column in the Presence Matrix $M_p$ can move up (see Figure VI-13).

We detail now the procedure that is used in order to select modules for possible motion in a 3x3 domain. For simplicity of presentation, we consider here only elementary motion (we do not consider push, pull and carry motion). Starting from initial state given by the Presence Matrix, the algorithm computes possible motion as a tree structure (see Figure VI-14). When similar states are obtained like case 5 that is similar to case 4, the computations are stopped on that branch. The algorithm also computes the value of $\delta$ for each node of the tree. Finally, the algorithm selects the node with maximum $\delta$ value that will correspond to the final situation of a set of module motion. The distributed algorithm then communicates in sequence to the different modules in the square domain, the module motion they have to implement in order to obtain the situation corresponding to the node with maximum $\delta$ value.

Figure VI-14 Tree of possible motions

Special case with 5x5 domain.
We note that with 3x3 matrix the distributed algorithm may not handle some special cases, like some motions with carry capability, due to the limited neighbourhood. This is the reason why we have also introduced a 5x5 matrix. We recall that the objective of the distributed algorithm is to construct a set of adjacent modules from the input I to output O progressively.

We present now part of the pseudocode that computes module motion in the 5x5 case.

------------------------------------------------

Input: Positions of modules in the 5x5 domain

Procedure:

counter = 0

PriorityQueue = [initial positions of modules in 5x5 domain]

While counter <= 20:

(1) From the PriorityQueue, pop the position_of_module with the maximum Objective Function Value $\delta$

(2) Insert all possible next-move positions from the popped one to the PriorityQueue, with their corresponding Objective Function Value, as well as the corresponding history to make such movements.

(3) Increase counter by 1

End While

Return: positions_of_modules with the minimum Objective Function Value in the PriorityQueue

------------------------------------------------

A complete solution of the shortest path problem via the distributed algorithm presented above is displayed on the Figure VI-19.

VI.4. Simulator of Smart Modules (SSM)

We have designed and developed a Simulator of Smart Modules (SSM) in order to test and validate our distributed algorithm that solves the shortest path problem. This simulator permits one to display
the position of modules and their motion when the algorithm is implemented. SSM is a Python-based simulator which can work on Windows, Linux, and IOS.

### VI.4.1. Interface

The positions of the modules, the module motions, and modules in the domain resulting from the elections are displayed in real-time.

The simulator interface is divided into four areas (see Figure VI-15), that is Module display area, Parameter setting area, Operating area, Results area. The simulator interacts by clicking the mouse, such as setting the input, selecting the modules, selecting parameters, clicking on the Pause, etc. We detail now the different areas.

**Module display area**

This area displays the position and status of the modules in real time, up to 14x20 modules can be displayed here.

**Parameter setting area**

a). The domain around elected module can be chosen as 3x3, 5x5, or both of them.

b). Push enable, Pull enable, Carry enable. The three buttons permit one to add or withdraw the three capabilities mentioned in section VI.2. By enabling or disabling these capabilities, the effects of these three capabilities can be directly observed from the module display area and the number of elections and steps.

c). The bottom All connected imposes that all modules are connected during the movement, due to hardware limitations.

d). When the input and output are not in the same horizontal or vertical line, the shortest paths is bounded by two polylines. Both of the two polylines will be displayed if the select button “Two paths” is active; on the other hand, only one randomly chosen polylines will be displayed if the select button “Two paths” is inactive.
**Operating area:**

This area is related to the operating mode of the simulation, three buttons are shown here, that is Run, Pause, and Reset.

**Results area:**

This area allows the observation of the total numbers of elections and the number of module motions (steps). These types of data directly reflect the efficiency of program execution under different conditions.

VI.4.2. Usage of SSM

**Step 1:**

Setting the simulation parameter in the setting area.

**Step 2:**

In the module display area, Input (beginning of the module structure shown as IN) will be set by the first click of mouse, Output (end of the module structure shown as OUT) will be set by the second click, both of them appear in red. After Input and Output, each click will add a module in the corresponding cell in yellow, so that the initial shape can be set. When setting the initial shape, we note that Input must be occupied.
Figure VI-16 shows an example with Input and Output, and initial shape. The Input is occupied by a module; this module will become red when the simulation is running.

**Step 3:**

Click Start to begin the simulation. If the initial shape is set incorrectly or the simulation is finished, then we have to click Reset to return to the initial state as shown in Figure VI-15. The simulation also can be paused.

![Figure VI-16 Setting the Input (occupied by module 3), Output and initial shape](image)

In order to facilitate the observation of the simulation, each election is also displayed. In particular, all the modules in the area around the elected module are displayed in green (see Figure VI-17). In this example, module 10 at the center of the 3x3 domain is elected.
VI.4.3. Results

This simulator not only allows us to observe the experimental results but also helps to validate the distributed algorithm experimentally. Figure VI-18 gives simulation results for two shortest path problems. Number of elections and steps also displayed. Figure VI-19 displays a complete solution with details on election processes.
Figure VI-19 Complete solution of the shortest path problem via distributed algorithm displayed with SSM simulator
VI.5. Conclusion

Push and Pull capability are necessary. Without Push or Pull capability, it is generally impossible to find out the shortest path between input I and output O. Without Carry capability, in most cases, it is possible to complete the task, but more elections and steps are needed.

Another conclusion of this chapter is that many trajectory optimization problems between the Input and Output; with shortest path length N−1; can be solved in finite time with at most N modules by the proposed distributed algorithm. The extra module which is called Support is used to provide a support surface for the last module of the path.

Through experiments, we found out also that if we consider 5x5 domain, both the number of elections and steps can be reduced as compared with the situation with the 3x3 domain. Moreover, the more the number of modules, the advantage is more obvious.

Considering a combination of 5x5 and 3x3 domains is generally better than considering only 3x3 domain. As a matter of fact, using 3x3 domain may not permit the distributed algorithm to converge to the solution of the shortest path problem while 5x5 domain permits the algorithm to take into account a larger neighborhood and carry out more sophisticated module motion.

With a larger domain, some initial tricky situations can be considered with success, like shown in Figure IV-20, and video [3]. The line consisting of modules 3, 4, 5 and 6 is out of the range of 3x3 matrix. There is only a line inside the matrix centered on module 5 or module 6, no Support; so, these modules cannot move. On the other hand, one 5x5 matrix can cover module 3, 4, 5, 6 and 7; module 7 can be seen as the Support.

Figure VI-20 Initial shape
References in Chapter VI


Chapter VII. Conclusion and Perspectives

VII.1. Conclusion

For most institutes that make research works on modular self-reconfiguring robotic (MSRR) system, scientific contributions are either on hardware or on software; they seldom focus on both. Also, robotic systems like conveyor may not continue to be efficient when changes in goals or environments and faults occur.

This thesis is an extension of the Smart Surface and Smart Blocks projects which aimed at building smart conveyors. Based on this goal, the research work that been carried out in this thesis proposes a MSRR platform, whose name is DILI. The main work focuses on both hardware and software, which contains actuator design and their numerical simulation, fabrication, tests, design of distributed algorithm, and simulator of our MSRR platform. In the physical composition, actuation and connection systems are two important parts of a modular robot. Typically, actuators occupy more than 50% of the volume and weight of modules and thus are major obstacles in downsizing modules.

In this manuscript, we have presented simplified electro-permanent (SEP) magnets along with a new concept of a linear motor. SEP magnets can change the magnetic field direction. The new linear motor can achieve both motion and connection with only one system and does not require energy consumption while connected. This linear motor provides a miniaturization solution for other modular robots. By using this motor, the complexity of the structure of modular robot systems can be greatly reduced; the size of the robot modules can also be greatly reduced. Moreover, this motor can save energy, which is important for robots at small scale. We have also proposed a model of SEP magnet in COMSOL Multiphysics; the numerical results play a guidance role in designing and validating SEP magnets. We have designed the circuit and structure of DILI and tested its performance via a series of experiments, DILI module can slide along the surface of other modules with three modes: the fastest mode, the stable mode, and the enhanced mode.

Modules of MSRR have limited computing and sensing capabilities. Thus, control algorithm must be able to adapt to the actual compute power and motion ability of the modules, and take into account
the coordination of motion of the modules to ensure the regular overall macro motion of the whole system. We have introduced a distributed algorithm for DILI in order to set up a smart conveyor; the distributed iterative algorithm looks for a solution that gives the shortest path between given input I and output O; at the same time, it tries to minimize the number of module motion. The distributed algorithm relies on several steps, like step 1, the distributed election of a module that could be a good candidate for possible motion to the output O; step 2, definition of a square domain centered at the selected module and consider the possible motions of modules in that domain. Our distributed algorithm is an exact method for the shortest path problem and a heuristic for the module motion problem.

Finally, in order to test and validate the distributed algorithms, we have developed a Simulator of Smart Modules (SSM) for DILI robot system. The simulator SSM is a Python-based simulator which can work on Windows, Linux, and IOS. This simulator permits one to display the position of modules and their motion when the algorithm is implemented.

We note that DILI modules may have a lot of applications. For example, they can be used in smart manufacturing (like smart conveyors for drug manufacturing or tiny systems, e.g. clockwork manufacturing). They can be produced for educational purpose or smart robots that evolve on difficult terrain. The concept behind DILI robot may also be used for programmable matter, e.g. furniture, tools, sculpture (art).

VII.2. Perspectives

Until now, we have built a MSRR platform which contains both hardware and software. Based on the current work, a number of research directions should be investigated in the future.

- Since the beginning of our project, the circuit of DILI module is apart from the frame; This limits the test with a large number of modules. In the next step, we plan to replace the 3D printed frame with a flexible circuit that will be placed in the frame, just like the Pebbles robot system.
  - Sensing capabilities and communication capabilities should be included in order to detect adjacent modules and communicate with them respectively.
• A type of actuator should be selected; These actuators will be placed on the top of DILI module to build a device like a smart conveyor.

• Using SSM simulator of DILI robot will permit us to address the issue related to the 3D motion of modules. Each DILI module is a cube; in the future, we plan to work on the design of modules having 3D motion capability. This will certainly lead to rearranging the SEP magnets and NdFeB magnets.

• Comparing with the connection mechanism, the connectivity of SEP magnet is relatively weak. We can add a mechanical connection structure to DILI, such as a gripper, but the gripper is used only for the final fixation, and the gripper is not needed during module movement. Comparing with the robotic system with only mechanical connection system inside, this hybrid design can not only provide a stable connectivity but also can save energy, save action time and reduce the complexity of the algorithm.

• Distributed algorithm that permits one to reconfigure the set of modules when a fault occurs in the system should be proposed.

• Also, the scalability of distributed algorithms should be studied in order to deal with a large set of modules.
List of publications and demos

- **Li Zhu**, Didier El Baz, Huangsheng Ning. Survey on Air Levitation Conveyors with possible scalability properties [C]. The 15th IEEE International Conference on Scalable Computing and Communications, 2015, Beijing, China, August 2015, 802-807.


- Didier El Baz, **Li Zhu**. Smart systems, the fourth industrial revolution and new challenges in distributed computing [C]. Parallel Computing Conference 2017 (ParCo 2017), keynote speech, to appear in the proceedings of the conference, Bologna, Italy September 2017.

- **Li Zhu**, Didier El Baz. DILI, a distributed modular robot with one system combining locomotion and connection. In preparation for submission to a journal.

- Video of DILI module carrying out the rectilinear motion: https://youtu.be/kxIJRraiZQI.

- Video of DILI module carrying out the push, pull, carry and load functions: https://youtu.be/Xs5-HF0M6JU.

- Video of SSM simulator: https://youtu.be/Eqg95hqfq60.