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Albert Jozsef Enyedy
Worcester Polytechnic Institute

Felix A. Sanchez
Worcester Polytechnic Institute

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Swarm Scaffolding MQP

Albert Enyedy & Felix Sanchez

ajenyedy@wpi.edu, fasanchez@wpi.edu

Department of Robotics Engineering
Worcester Polytechnic Institute

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I. ABSTRACT

In this paper we explore the implementation of autonomous robotic scaffolding using custom basic building blocks and intelligent scaffolding blocks. The scaffolding blocks interact with each other on the same level of authority in order to coordinate with the robot driving on top of them to construct a structure autonomously, following different building algorithms. While the robot itself remains fairly simple and unintelligent, the scaffolding blocks communicate as a swarm in order to direct it, resulting in a dynamic swarm of scaffolding blocks capable of self organization and construction optimization.

The first iteration of this system was developed in 2018 by a Major Qualifying Project (MQP) team at WPI. This project focused on the improvement of the robot and blocks for future implementations of swarm robotic concepts. The robot’s ability to manipulate blocks (scaffolding or building material) and to traverse the new, improved scaffolding blocks (SBs) was upgraded. Upgrading the communication interface used by the blocks was crucial in order to implement swarm robotic concepts, thus we focused on and improved it. The shift away from a fully 3D-printed block allowed for modular designs and quicker manufacturing of the blocks. The robot’s pickup mechanism was made to fit the new blocks and uses a novel permanent magnet manipulator. Results showed that separate parts of the project operated with reasonable success after performing several unit tests. These included picking up and putting down blocks, line following across blocks, block-to-robot communications. The unit test that presented the most difficulty was the ability to turn accurately due to the line sensors being unable to detect the line at fast turn speeds.
II. INTRODUCTION

Synergy and coordination are crucial parts of multi-entity projects. One of the best examples of the importance of efficiency through cooperation is in the construction industry. The construction industry accumulates an estimated loss of $15.6 billion per year due to “the lack of interoperability associated with construction projects” [1a]. As with most physically-intensive industries, there is also an increased risk to human life, as shown in Fig. 1 with construction workers in a minimally-secured environment high above the ground. A total of 4693 worker fatalities in private industry occurred in 2016, of which 21.1% (991 lives) were in construction [2a]. Based on these trends, there is a demand for newer and more efficient ways to build future structures in order to reduce project time, decrease the endangerment of workers, and cut costs overall.

Swarm intelligence, robotics, and smart materials offer solutions to this overarching problem by removing the human risk in construction. Groups of robots can work together using advanced algorithms and intelligent scaffolding to assemble buildings in a more safe, reliable, and consistent manner than humans. A group of cooperative robots is shown in Fig. 2 self-assembling to become a larger system, aiding in navigating terrain with large gaps and allowing the robots to collectively push heavier objects than a single one of them could push. In addition to construction, robots can be used to complete maintenance and repairs on decrepit buildings that would endanger human lives. For routine operations on buildings, teams of construction robots can remain on standby for lower cost than human construction crews and can be equipped with only the necessary equipment to complete their work, increasing efficiency. Smart materials offer self-assembly capabilities and often provide teams of robots with the navigation and data they require to construct structures. An example of smart materials could
involve a custom unit of building material that has electrical connections and QR code stickers on its surfaces that would be used to guide robots throughout their construction of the structure. High-tech solutions such as these can potentially become the norm in the future because of advances in robotics such as additive manufacturing, prefabrication methods, and swarm robotics.

![Fig. 2. A swarm of swarm-bots self-assembling](image)

However, these systems can have high cost as well, depending on their implementations. Construction robots can be large, complex, and expensive, and in the event that one would fail the system would lack the robustness to continue construction effectively. Complex robots can reduce redundancy if there are not enough spare robots to take the place of those that break down on the job, a reasonable concern given the dangers of some construction environments. Using a swarm of many simple robots could have high cost depending on the method of commanding them. Many swarm construction methods currently use custom smart building material blocks, as shown in Fig. 3, that provide resources for navigation such as lines, QR codes, or specific surface designs to prevent robots from traveling off of their intended paths. Once the structure is completed, the smart material that was used cannot be reclaimed and remains at the build site. Thus, such systems increase cost by requiring new sets of custom smart material for each new build site and they limit the available applications for the systems by requiring the custom material as opposed to using common building material such as cinder blocks.
To develop a more optimal construction solution using swarm intelligence, robotics, and smart materials, we propose a system using simple robots with removable smart scaffolding material. Such a system would use custom smart scaffolding blocks that the robot would place to provide commands in an area of the build site. Thus, the robots remain simple since their actual construction planning is performed off-board on the blocks and the robots need only receive the instructions. The simplicity of the robots allows for simpler production of many of them, increasing the redundancy and thus the robustness of the system in the event that a robot fails during the construction process. However, the key element of the system is the reusability of the scaffolding blocks because they remain external to the structure and are removed once the structure is complete, mitigating the high cost of producing new smart material each time a new build site is visited.

A. Problem Statement

The 2018 MQP team designed the first iteration of a swarm construction system using intelligent scaffolding that would strive to implement a novel approach utilizing smart materials and swarm construction in order to not have the smart material remain in the final structure. They designed smart blocks to serve as the intelligent scaffolding, and a simple robot that could receive commands through colored LED signals from the smart blocks. The team also developed several different successful algorithms for constructing 2D structures using their swarm construction system in simulation, however their physical system of robot and smart blocks required improvements to assemble the structures successfully.

However, the physical system of the 2018 MQP team had a few weaknesses. Most apparent was the inability to accurately manipulate the SBs due to their vertical ball screw mechanism. There
was too much swaying and backlash that resulted in high amounts of deviation when attempting to pick up and put down blocks. The blocks themselves also lead to issues with navigation as the holes required for the pick up mechanism would interfere with the wheels of the robot as it drove over them.

Our task was to specifically improve upon the work that the 2018 MQP team began by changing the physical design of the robot and blocks to enable successful construction. The main focus of the redesign would center around the main weakness of last year’s project, the hoist mechanism. This would cascade into a redesign of the block to match a new pickup mechanism as well as change the design of the robot to carry both the new block and manipulator.

B. Contributions

We designed a system of smart scaffolding blocks that issue commands to a simple robot to assemble 2D structures. We based our design on the strengths of the 2018 MQP team’s designs, and improved upon their designs’ weaknesses. The scaffolding and material blocks were improved overall; the hoist mechanism was redesigned for more consistent block manipulation, and the robot was changed to match the hoist redesign.
III. RELATED WORK

Swarm robotics has many applications in assembly, whether for structures or themselves. Groups of robots have worked together to build structures using specific, interlocking building blocks, smart blocks, and the assistance of intelligent scaffolding for navigation and organization. Some robot swarms can also self-assemble, allowing them to traverse difficult terrain and prevent each other from falling off of ledges.

A. The TERMES Project

Through the use of biomimicry, low-level rules were established to accomplish high-level goals with autonomous termite inspired robots [3a]. Structures could be constructed using building plates being placed by robots that only had onboard sensing. Due to the synchronous physical design of the robots and plates, the TERMES project allowed for building in the third dimension like real termites building mounds. However, the project is limited by requiring special blocks for the robots to assemble structures with and to travel across, preventing the system from being used with common building material found at everyday construction sites. Our project takes inspiration from the TERMES system, but by using intelligent scaffolding to guide assembly our system can more easily be adapted to assembling structures using common building material instead of lab building material.

Fig. 4. TERMES project robot
B. Stigmergic Blocks

Computer vision, NFC blocks, and electromagnets were used in this research in order to have a robot autonomously build 3 dimensional structures without the need of scaffolds [4a]. The autonomous robots are incapable of traversing over the smart blocks but use a forklift style lifting mechanism in order to stack and arrange the smart blocks. Colored LEDs are used to signal block-to-robot communication using a mounted camera on the robot. The end effector of this robot relies on the use of electromagnets to pick up the blocks which use spherical magnets to connect to each other and the robot’s manipulator. Both the pickup mechanism and smart block connections influenced the design process for our project. Their vertical manipulation of the block as well as use of LED color communications in part inspired the way blocks are manipulated for our project. Along with previous work on this project, the LED signaling is proven to be a useful and efficient medium to convey simple status information.

![Fig. 5. Stigmergic blocks with manipulator robots](image)

C. Intelligent Scaffolding

Correll et al. [5a] at the University of Colorado, Boulder, have performed research on intelligent scaffolding as well in 2011. They only developed an algorithm, however, and performed their tests in simulation rather than with physical robots. They show “that intelligent scaffold blocks can assemble any finite structure... using only three intelligent scaffold blocks in simulation”. Their intelligent scaffolds connect to the basic building blocks and each other, requiring at least one scaffold to be attached to another (a minimum of two scaffold units). The scaffold groups would then move along the structure, communicating to each other via messages that indicate...
changes on their faces. A finite state machine can be used to model the assembly process, in which the placement of a block is an exit state. A similar finite state machine was designed for this project to allow for a “step” based approach when communicating color sequence commands from the block to the robot via the LED on top of SBs and the color sensor at the bottom of the robot’s base.

![Finite State Machine Diagram]

*Fig. 6. Demonstrating the scalability of intelligent scaffolding*

### D. Collective Construction with Robot Swarms

Passive or intelligent blocks were used to guide a swarm of robots built based on previous swarm robotics projects and nature’s swarm construction experts, the termites. The concepts of convention (all robots follow same rules) and stigmergy (storing information in the environment) were implemented by Werfel [6a] to coordinate using the blocks. The two main navigation methods were using landmarks in the building of the structure to enable using passive blocks for navigation by having the robots recognize unique features of the structure, and using writable (intelligent) blocks utilizing RFID tags to store data for the robots to read. The overseer could design a high-level *shape map* to designate where the blocks should ultimately be placed, without specifying how the robots should transport them. The robots would then build starting from a seed block and use either the passive blocks or intelligent blocks method to complete the structure. To build with multiple materials, rules depending on material would be developed. If the structure has areas that can have varied placement of blocks (shape adaptivity), then a few constraints can be specified and the robots would decide where the blocks go based on the environment.
Fig. 7. A simulation of 10 robots building a prespecified structure in 3D with 2 types of blocks

E. PolyBot: A Modular Reconfigurable Robot

Another form of swarm robotics includes smaller, reconfigurable robot units that combine to make a larger, complete entity developed by Roufas et al. [7a] as a modular robotic platform. The robots’ ability to assemble in many forms permits multiple options for crossing a variety of terrains, as shown in Fig. 8. The system excels at tasks which require versatility, such as “tasks in unstructured unknown environments”, and has the ability to repair itself due to the simplicity of replacing modules. The Polybot makes use of this design paradigm by using a segment module and a node module, each of which have limited performance alone but can perform complex tasks when combined. Similarly to our project, an SB alone is unable to do much however by combining several at once, they are capable of effectively guiding manipulator robots above them regardless of their configuration. With some future work, scaling this modular and reconfigurable approach to a vertical dimension will allow for complex structures in 3D allowing for communication among all blocks in the system. The PolyBot modules communicate using “(Controller Area Network) CAN bus standard”. Module connections send both power and communications between modules, and the PolyBot receives its power from a tethered power supply. The 2018 MQP team utilized the CAN bus standard however a switch to I2C was implemented as a more simple solution for interblock communications as there were already established libraries to transmit packets of information between the Arduino Nano’s that were placed in the smart blocks.
Fig. 8. Polybot showing reconfiguration, 1) using efficient rolling track gait, b) using obstacle crossing earthworm gait, c) using stable spider gait, 4) using a realistic spider gait

F. Autonomous Self-assembly in Swarm-bots

Established rules and multi-robot communications for our project were inspired from the work by Dorigo et al. [8a] specifically on their self assembling swarm-bots. The robots used, called Swarm-bots, were capable of grasping onto one another and would localize from a central pillar and other robots. They would scan and find a nearby robot and attach themselves, self-assembling into a single unit.

The Swarm-bots were capable of doing this in part of the rules their sensors would follow such as correcting for errors when grasping each other or maneuvering. LED’s on the robots would indicate their status and cameras would see the surroundings and aid in the decision making of the robots. The speed at which the robots would self assemble can be measured in seconds in groups as large as 16, proving that their algorithm for accurately measuring each robot’s surroundings was impeccable.

The Swarm-bots were also made to handle rougher terrain than flat floors such as studs, further complicating the environment and the task of self-assembling because of the random angles robots would find themselves in. By utilizing similar rules as this project, we created rules for the
manipulator robots to follow when interacting with the blocks giving them commands. We also were impressed by the LED status of the robots and implemented this as a color status light on the blocks in order to tell if a new block was added or removed to show that the system of blocks was cognizant of changes with its structure.

Fig. 9. Swarm-bots self-assembling into a single unit
IV. METHODOLOGY

A. Previous Year’s MQP

The first year of the swarm scaffolding MQP was completed during the 2017-2018 academic year, and the MQP team set up the initial robot, scaffolding blocks, and algorithms [9a]. The robot would receive commands from the scaffolding blocks by reading the colors from the RGB LED on top of each scaffolding block. The algorithm would determine how the robot should build the desired structure.

The scaffolding block design was fully 3D-printed and was 2 inches high. The block had holes in the top for the robot’s gripper to attach to, as well as an RGB LED in the center of the top surface for the robot to receive commands from. The block’s surface had white tape lines on top to guide the robot through line following, and copper plates and pogo pins to enable interblock communication, as shown in the CAD model in Fig. 10. For blocks to communicate with each other, CAN communication protocol was implemented and signals were transmitted using the copper plate and pogo pin connections.

The pogo pin and copper plate system worked as intended, allowing the CAN communications to travel between blocks. However, the block design had trouble connecting with other blocks due to the block interlocking mechanism the team had designed which allowed little room for error when placing blocks. The robot had trouble manipulating the blocks due to the high weight of the fully 3D-printed block frame, as well as the precision required by the holes on top of the blocks. Each block also required at least 24 hours to print.
The robot design used differential drive to maintain a turning center about the center of the robot with acrylic skids in the front and back of the robot chassis for support. To manipulate blocks, the team used a claw gripper that would be moved vertically using a lead screw, as shown in Fig. 11. For sensing and navigation the robot used two line detection sensors, one in the front and one in the back of the robot, as well as a color sensor located at the turning center of the robot. The robot navigates using the line detection sensors to line follow along the top of blocks, and receives commands from the block’s RGB LED using the RGB sensor.

The robot could navigate successfully on a test board, but not on top of the scaffolding blocks due to the robot becoming stuck when passing over the holes on the top of the blocks. The line following algorithms for navigation allowed the robot to complete commands as intended. However, due to the design of the lead screw system, the robot cannot pick up the blocks properly. The claw attachment to the lead screw ends up pitching forward when a load is applied, causing the mechanism to bind, preventing it from lifting. The MQP team also reported that the robot was too large to properly traverse over the blocks.

The algorithm starts by setting up a spine of scaffolding blocks through the center of the proposed structure, beginning at a seed block where the robot starts. The robot only moves on top of scaffolding blocks, thus to reach various locations in the structure the robot sets up branches of scaffolding blocks and then removes them once all build material blocks are placed that are accessible from that branch. A simulation of the algorithm is shown in Fig. 12.
The algorithm of the MQP successfully assembled structures in simulation. The success of the algorithm allowed for this year’s MQP to focus only on the physical design of the system.

B. Requirements

The blocks required a streamlining of design to make them easier to manipulate and faster to assemble, attainable by reducing the amount of material required and switching to a modular design to increase the efficiency of 3D printing and assembly. The blocks required a robust connection method, allowing the robot to have increased room for error when placing blocks. An alternate method for manipulating blocks was required to remove the holes on the surface of the blocks which prevented the previous year’s robot from traversing across the top of blocks.

The robot required a new system for manipulating blocks that would not bind. The manipulator required an alternative method for manipulation than a claw to allow for a smooth top surface on each block. The robot required a smaller frame design to increase stability while turning and to enable the robot to carry blocks above its turning center.

The algorithm required only minor tweaking to increase efficiency. The previous year’s algorithm allowed the robot to only move across scaffolding blocks, but the robot should be able to traverse building material as well. The ability to move across building material blocks reduces the quantity of scaffolding blocks required by allowing the system to space them out throughout the structure, assigning each scaffolding block a region of control. To accommodate the algorithm change, building material blocks require electrical connections to transfer signals between smart blocks and a new system for commanding the robot is required that allows for
multiple instructions to be stored in sequence, providing commands to the robot while it traverses building material blocks.

C. Scaffolding Blocks

The new SBs are based on improving the design of the previous year’s MQP. The connection between two SBs is formed via pogo pins and copper plates in order to transmit power and data throughout the assembled structure, similar to [9a]. The connection plates are on the sides of the SBs with one side being an origin side where power and data is expected to be coming into the block from another SB. If the SB is the first block, then power from an external source will connect here. The SBs have four lightweight, 3D-printed legs as corner pieces with neodymium magnets inside to ensure secure connections with other SBs. The overall height of the block was reduced in an effort to lessen the load that the robot must manipulate as well as cut down on assembling time because they are 3D printed. The top plate is an 8” x 8” opaque, black acrylic sheet. This is in order to permit reliable line following and LED reading for the robot. An Arduino Nano board is attached on the underside of the acrylic plate to control the LEDs and the SB’s I2C communication with other SBs. A large neodymium magnet is also underneath the center of the acrylic so that the robot can pick up the SB using its magnetic linear actuator along with the RGB LED used to communicate with the robot. An example of the prototype model of one of these SBs is shown in Fig. 13 with the final physical model in Fig. 14.

![Fig. 13. Final scaffolding block CAD](image)
D. Robot

To address the size problems in [9a], the robot has a 7” x 7” drive base and a turning center about the midpoint of its wheelbase. The robot employs a four-bar linkage with a rack-and-pinion linear actuator end effector, shown in Fig. 15, to avoid the locking that prevented the lead screw from functioning properly in [9a]. The linkage is attached to the base of the robot in such a way that SBs can be held above the turning center of the robot for transport. The end effector attaches to blocks with its neodymium permanent magnet, and detaches from blocks by lifting the magnet off of the block surface using the linear actuator.
The permanent magnets allow the SBs to have smooth surfaces where the robot will be driving on, making navigation more reliable. The robot is controlled by an Arduino Mega, and driven by two DC motors connected to an H-bridge. It employs two line sensors on the underside of the chassis to track the white lines on the top surface of SBs in order to move from one block to the next and keep track of the number of blocks it has traversed. The mounting fixtures for components are 3D printed while the base of the robot is laser cut out of ¼ inch birch wood. A color sensor is mounted in the center of the underside of the robot in order to detect the RGB LED’s color emitted by the hole in the center of the SB’s. The color sensor is crucial for communications between the blocks and the robot, as the RGB colors on the smart blocks are the signals that command the robot.

E. Budget

Worcester Polytechnic Institute has provided us with $500 to complete this project. We have developed a basic overview of our expected costs in Fig. 16. We planned to use roughly $300 of the money provided to us, and kept within that estimate. Left over funds were used to purchase additional supplies for next year’s MQP to have more base materials to build off this project. Materials such as more electronics and acrylic for block creation were made sure to be bought so that if the next group wanted, they could create more blocks matching the ones in this project.

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<th>Component</th>
<th>Price Estimate</th>
<th>Quantity</th>
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<td>$9.90</td>
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<td>Rechargeable NiMH Battery Pack: 6.0 V</td>
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<td>2</td>
<td>$30.30</td>
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Fig. 16. Proposed budget
About half of the used budget was spent exclusively on the robot (components highlighted in red), while the remaining costs were either spent exclusively on the blocks (highlighted in green) or on components for both systems (no highlight). Components such as the line-following sensors and the color sensor were already available to us at no extra charge, taken from the robot of the previous year’s MQP team, thus we do not consider those components’ values in the budget.
V. EXPERIMENTAL EVALUATION

A. Block Design

We optimized physical properties of the blocks by testing various materials and designs. We aimed to produce a lightweight, modular design that required a reasonable amount of time to print and had a high-contrast surface for line following. The design would incorporate magnets of appropriate strength for connecting blocks to each other and connecting the blocks to the robot’s magnet linear actuator.

Originally, 1” diameter neodymium magnets were placed in the legs to connect blocks together. After having two legs printed and assembled, a simple unit test where they were connected resulted in difficulty in separation even with human hands. This proved to be too strong of a connection and a shift to smaller magnets was implemented. These new 0.25” diameter neodymium magnets proved strong enough to hold a connection with one another while still being easy to separate when tested in the same fashion as the 1” diameter magnets. To anchor the magnets in place, due to their small size, a support piece was added behind them, as shown in Fig. 17.

![Redesigned block magnet holders](image)

The legs using the design shown in Fig. 17 took roughly two hours to print, so we decided to reduce the print time and material used by decreasing their height from two inches to one inch. This height reduction decreased the weight of each leg by 5 grams, measured using a digital scale, reducing each block’s weight by 20 grams total, as shown in Fig. 18.
To determine which material we would choose for the surface of the scaffolding blocks, we recorded the average of 10 light sensor values per test for each surface we considered, shown in Fig. 19. We placed the robot on top of each surface, and read the values from both the light sensor in the front (LS[0] in Fig. 19) and the back (LS[1] in Fig. 19) of the robot.

![Fig. 19. Block surface light sensor readings](image)

The results show that a combination of white electrical tape lines on a black acrylic surface would provide the greatest contrast. We decided on this combination of materials in our design.

### B. Block Electrical Connections

A crucial aspect of this aspect was the ability to reliably transfer data and power through the blocks. The past implementation of the SBs had room for improvement such as changing the approach when connecting blocks, standardizing the quality of the connections throughout blocks, and organize the connections of the wires within the blocks.

Two test blocks were needed for this unit test. Power and ground were supplied to the block on the left on two pins followed by the matching pins on the right connected to a resistor in series with an LED. If the LED powered on once the blocks were magnetically locked then the connection was stable, however if the LED did not turn on or was flickering this showed that the connection is unstable. Two versions of the connections were tested. The first version had two

---

![Table: Block material combinations and corresponding weights](image)

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<th>Part</th>
<th>Individual weight (grams)</th>
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<td>100</td>
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<td>Top (Birch)</td>
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<th>Combinations</th>
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</table>

*Fig. 18. Block material combinations and corresponding weights*
plates and two pins are on each side with their opposite side on the other connector. The second version had 4 pins on one connector and 4 plates on the other connector.

We determined through experimentation that the pogo pin and copper plate connectors created a sufficient electrical connection for the blocks to communicate effectively. As seen in Fig. 20, the pogo pins and copper plates are positioned such that they can connect to other blocks adjacent to them, with inclined planes leading up to the copper plates to facilitate separating blocks. Fig. 20 also shows the blocks connected, turning on the LED to indicate that power is traveling between the blocks through our pogo pin and copper plate connections. While both versions of the connectors worked, it was found that the second version was more robust to disturbances and manufacturing errors.

![Fig. 20. Pogo pin unit test with version one of the connectors](image)

**C. Arduino Communication**

We ensured that the I²C communications would recognize newly added blocks in the system effectively through unit testing. The I²C communication between SBs was tested by setting up two Arduino Nanos next to each other and connecting them via two pins simulating a block connecting to another block. SBs are programmed to be “masters” if they detect no other SBs on their I²C network but “slaves” if there is a constant “assignment” message being broadcast to all new SBs. They are programmed to wait for each other and sync up in order to distribute the proper commands throughout the assembled structure of SBs. Parallel power and data transmission was also tested via connecting five Arduino Nanos to each other in parallel and on the same I²C network. The results were that the Arduino Nano’s were capable of connecting and self organizing into Master/slaves autonomously by listening to the established I²C network.
Data transmission was in the within 10 ms across the entire platform and adding/removing blocks from the system was robust and alerted the other blocks of the change in structure.

**D. Linear Actuator Magnet**

We ensured that the magnet for picking up blocks was strong enough to lift blocks consistently without being too strong to let go of the blocks through testing. For picking up the blocks, we tested the 0.25” diameter magnet against the 1” diameter magnet by attaching each magnet to the surface of a block and manually picking up the blocks from the magnet, and found that the 0.25” diameter magnets were too weak to lift the blocks. Thus, we attached a 1” diameter magnet to center of a scaffolding block and attached one on the linear actuator. However, the 1” diameter magnets were difficult to separate without any spacing between them, so we performed a test to measure how much force would be required to separate the linear actuator magnet from the scaffolding block based on how many spacers separated the block magnet from the surface of the block. We taped magnets and the desired amount of spacers to the underside of the top surface of a block, and then used a spring gauge to measure the required force to separate the linear actuator magnet from the block surface. From the results of this experiment (shown in Fig. 21), we determined that 3 or 4 spacers would be optimal due to the greatly reduced force required for separating the blocks.

![Table showing force required to separate linear actuator magnet from scaffolding block](image)

**Fig. 21. Linear actuator magnet separation results**

**E. Reflectance Sensor-based Turning**

The ability to accurately turn on top of the blocks was important for aligning the robot for picking up and dropping the blocks. Utilizing the two reflectance sensor bars, each with 6 individual sensors, being able to turn the robot and have it stop after 90° was the desired end result.

Placing a robot on top of a block with the robot’s center in line with the center of the block, facing a side, the calibration of the sensor bars was the first command to run. It would determine a threshold between white and black as two of the sensors per bar would be on the white line and 4 would be on the black. After calibration, the robot was commanded to turn until a new white line was detected and to correct in order to center itself over the line.
We tested the effectiveness of our reflectance sensor-based turning on the black acrylic smart blocks with white electrical tape markings to determine if having the robot turn accurately without using encoders was a viable solution. After ten tests of starting the robot in the same orientation on the center of the block and having it attempt to turn 90°, the robot consistently turned within a few degrees of 90° or made an exact right turn, as shown in Fig. 22. To compensate for the undershooting of the turn, a small extra turn afterwards was added to ensure turning to the correct position.

![Robot turning test, notice the slight inaccuracy in the end position](image)

**Fig. 22. Robot turning test, notice the slight inaccuracy in the end position**

_F. Reflectance Sensor-based Block Traversal_

To travel between blocks the robot required consistent line following, which we tested by checking how many times the robot would successfully traverse a set amount of blocks using only the reflectance sensor for guidance. We set up three blocks in a row, and set the robot to drive straight, stopping at each block and correcting itself if it veered off course, as shown in Fig. 23.
The robot used line-following logic to travel along the path of white tape made by connecting the blocks, and would stop whenever it reached roughly the center of a block, indicated by the perpendicular strip of white tape running through the block’s center. Out of ten tests using this setup, the robot successfully drove across the blocks, stopping at each one, nine times.

G. Center of Mass (COM) Considerations

With the changes in both the robot and the block, new center of mass calculations were needed in order to consider the act of picking up blocks and moving around with them. The ideal situation would be that the robot maintains stable throughout the action of picking up the block which is when the greatest chance of the robot tipping over occurs.

The SolidWorks simulation of the robot and block showed that the center of mass was within the front section of the robot when holding the block however when the real robot was setup with a block it would tip over towards the front. Adding weights became the next immediate solution. Thus a battery to power the robot was placed towards the back which still tipped it over. Thus a secondary battery was added which proved to be enough to stabilize the robot.

Due to the high weight of the scaffolding blocks compared to the weight of the robot, distribution of weight became an important factor during block manipulation. We realized in early block manipulation tests that the COM of the unloaded robot was required to be towards the back of the chassis to keep the COM within the robot’s support polygon while the robot held a block. To shift the weight towards the back, two 6V battery packs were placed on the back edge of the chassis, which resolved the COM issues faced.
H. Block Manipulation

The robot’s hoist mechanism was tested for consistency to ensure that the robot could repeatedly pick up and place blocks successfully. To test the robot’s ability to manipulate blocks, we set up a test where the robot would pick up and put down the same block into the same location multiple times in a row, as shown in Fig. 24.

Out of 20 trials, the robot successfully manipulated the block 19 times. To achieve such a high success rate, we reduced the magnet distance from the acrylic surface on the blocks to increase the magnetic attraction between the linear actuator on the four-bar and the blocks. The high strength of the magnets at the reduced separation distance prevented the block from rotating while the robot manipulated it, ensuring that as long as the robot’s chassis was in the right position on a block, the robot would be able to successfully place the block down in the desired location.
V. CONCLUSIONS

The smart scaffolding block system performed as intended via separate unit tests, proving the system’s viability for constructing 2D structures. The pogo pin and copper plate connections between blocks, anchored by the magnets on the blocks’ legs, provide a robust communication channel for the I2C protocol. The magnetic end-effector allows for manipulating blocks with a reduced error. This system is a proof of concept for an advanced system of intelligent scaffolding blocks cooperating with manipulator robots for assembly. While having a few inefficiencies such as the way that the blocks and robots communicate, this project accomplished its goals of preparing for future work as well as proving the fundamental concepts of the swarm robotic scaffolding approach.

A. Future Work

A possible idea for the future of this project would be using NFC to communicate between the robots and blocks. This would eliminate the LED and color sensor, potentially simplifying the structure of SB’s and robots.

Building structures in 3D would be another future goal of the project. The process would involve changing the leg design to enable stacking SBs on top of each other and changing the algorithms. Currently, the pogo pin and copper plate system only allows for communication in 2D, but adding intelligent ramp blocks which serve as the seed blocks for each level of blocks above the first could allow expansion of the system without modifying existing block structure.

Expanding the system to use multiple manipulator robots simultaneously would improve the efficiency of the structure building algorithm. However, ensuring the robots would cooperate with each other and avoid collisions would not be a trivial task. The robots would require increased complexity, such as proximity sensors to avoid collisions, and the blocks capable of directing multiple robots in their network.

B. Lessons Learned

Several parts of this project were great teaching moments for us. For instance, we learned how bothersome it can be to operate with 3D printing tolerances, especially if using different printers and settings. In addition to tolerances, it was also made clear early on the Arduino Nano’s were simpler to use than similar Nucleo boards due to the Mbed online compiler needed to program them. Many libraries already existed that worked well on Arduino but were unstable or unavailable on the Nucleo boards.
On the subject of sensors, while the reflective sensor bars were useful for line following and turning, they require a 10 second calibration routine per sensor bar which seems like unnecessary wait time per test run. Adding encoders to the wheeled base is highly recommended for true accurate wheel manipulation as well as changing the motors in general to have more torque as the current ones are less than ideal due to their torque and tire choices.
References


