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3D Swarm Construction

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Abstract

"Robotic construction can drastically improve the efficiency and safety of construction. However, current robotic construction is limited by the types of structures robots can build and the ability for multiple robots to work collaboratively to build structures. This project aims to create an autonomous collective construction system in which two types of robots cooperate: construction robots and smart scaffolding robots. The latter robot type integrates electronics into building materials to create intelligent structures and allows for dynamic reassembling of existing components. In addition, we design a multi-robot collaborative building algorithm that showcases construction both with real and simulated robots. This project is developed so as to establish both a physical and simulated framework for future work with swarm construction algorithms."

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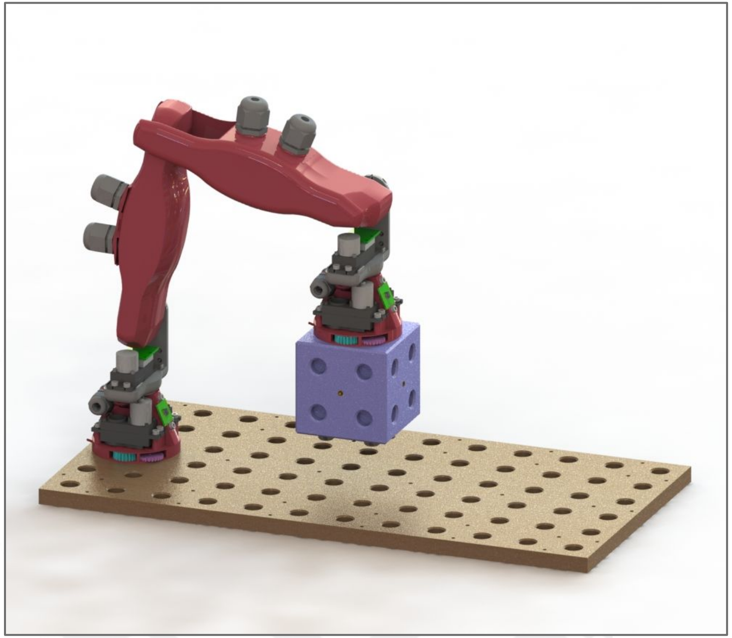


Introduction

Introduction

- Advances in automated construction can address future increased demand in construction
- The automation of construction can improve the safety of workers, especially in hazardous environments
- Multi-robot swarm systems can enable automated construction at larger scales
- Challenges exist in controlling swarms to achieve high-level construction goals

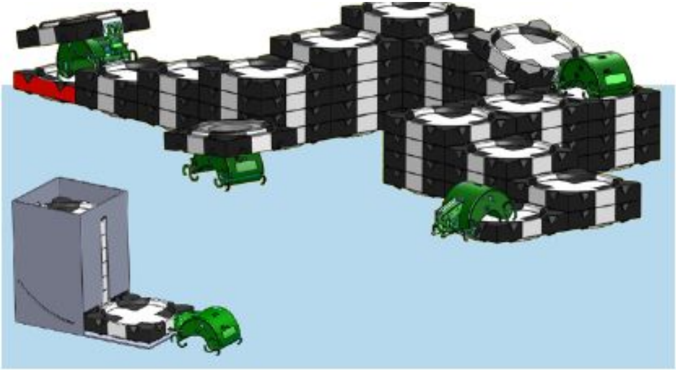
Project Novelty

- Formulated a swarm construction platform that builds in 3D with robots that are able to maneuver in 3D
- Produced robust algorithms that achieve desired emergent goals and are scalable to any number of robots
- Improved how robots use information provided by the structure to inform decisions regarding its construction

Prior Work

TERMES

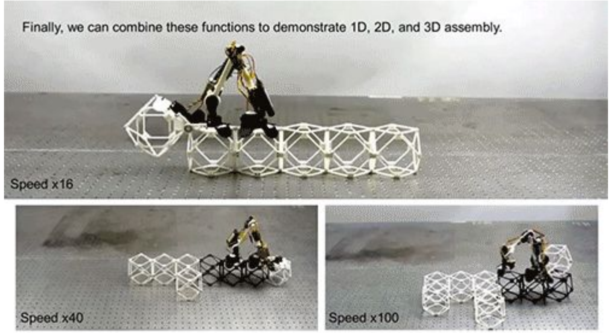
- Multi-robot construction system
- Decentralized system
  – Robots use local information and implicit coordination to successfully create a structure
- Limited to single-path additive structures
  – Physical limitation imposed by blocks and robots



Petersen, K., Nagpal, R., & Werfel, J. (2012). TERMES: An Autonomous Robotic System for Three-Dimensional Collective Construction. Robotics. doi: 10.7551/mitpress/9481.003.0038

BILL-E (Bipedal Isotropic Lattice Locomoting Explorer)

- Builds modular 3D structures comprised of cuboct lattice elements
  - Cubocts designed for low gravity
    - Lightweight
    - Affixed by magnets

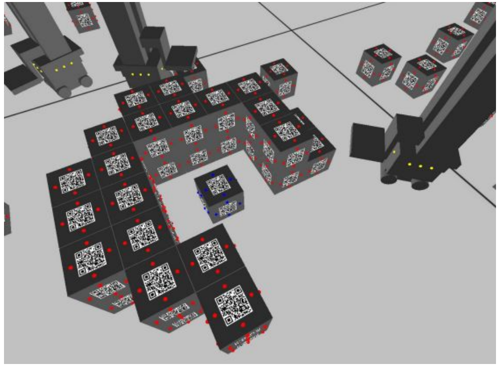


- Multi-DOF robot arm with end effectors to attach to its environment
- Holds and places building elements while navigating structure

BILL-E: Assembler Robots Can Build Large Structures with Little Pieces. (2019, October 17). Retrieved April 26, 2020, from https://www.roboticgizmos.com/assembler-robots/

SRoCS (Swarm Robotics Construction System)

- Near Field Communication (NFC) and computer vision establish an interface between robots and building blocks
- Robots use building blocks to communicate through stigmergy
  - Bio-inspired by ant pheromones
- Shape of assemble structure is not predetermined



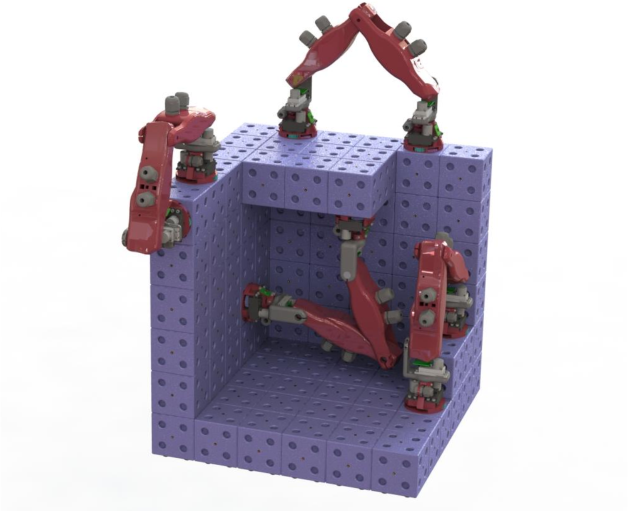
Allwright, M., Bhalla, N., El-Faham, H., Antoun, A., Pinciroli, C., & Dorigo, M. (2014). SRoCS: Leveraging Stigmergy on a Multi-robot Construction Platform for Unknown Environments. Lecture Notes in Computer Science Swarm Intelligence, 158–169. doi: 10.1007/978-3-319-09952-1_14

Mechanical Design

Design of Inchworm Robot

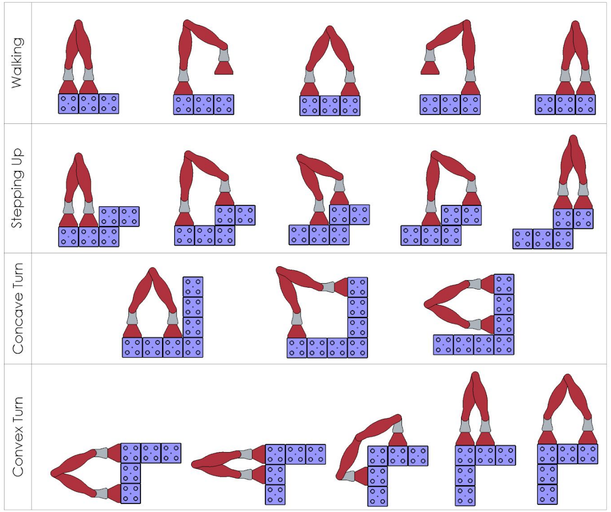
In order to build a wide variety of structures from block elements the inchworm robot must:

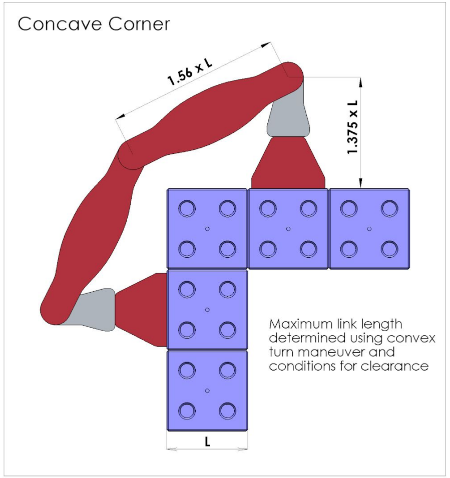
- Navigate structure to place blocks in arbitrary locations
  - Traverse in X, Y, and Z directions
  - Turn 90° to change direction
  - Traverse up and down
    - Concave corners
    - Convex corners
  - Step up and down a level
- Control block throughout the process



Linkage Lengths Analysis

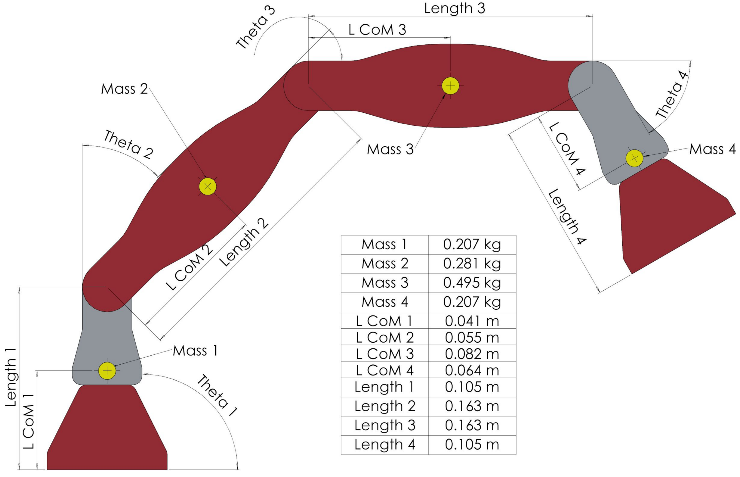
- Created mathematical model for inverse kinematics
- Calculated minimum link length for inchworm to minimize joint torque requirements
- Robot dimensions scaled based on block size





Robot Dynamic Model

- Established robot dynamic model using Lagrange's equations in order to estimate dynamic joint torques
- Estimated velocities and accelerations for traversal of structure
- Calculated maximum dynamic torque to be 17.5 kg-cm



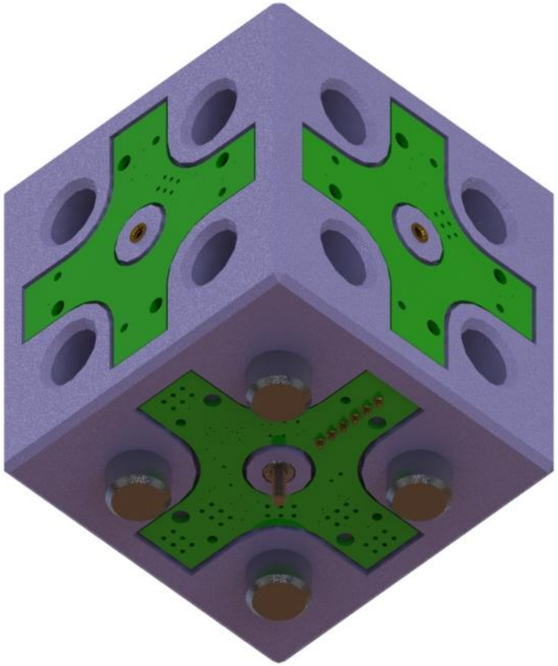
Mass 1	0.207 kg
Mass 2	0.281 kg
Mass 3	0.495 kg
Mass 4	0.207 kg
L CoM 1	0.041 m
L CoM 2	0.055 m
L CoM 3	0.082 m
L CoM 4	0.064 m
Length 1	0.105 m
Length 2	0.163 m
Length 3	0.163 m
Length 4	0.105 m

Joint Motor Specification

- Final robot design uses servos rated for maximum dynamic torques experienced with a FoS of 1.7
- Using 30 kg-cm hobby servos
  - Inexpensive
  - Readily available
  - Easily reproduced to create large swarms

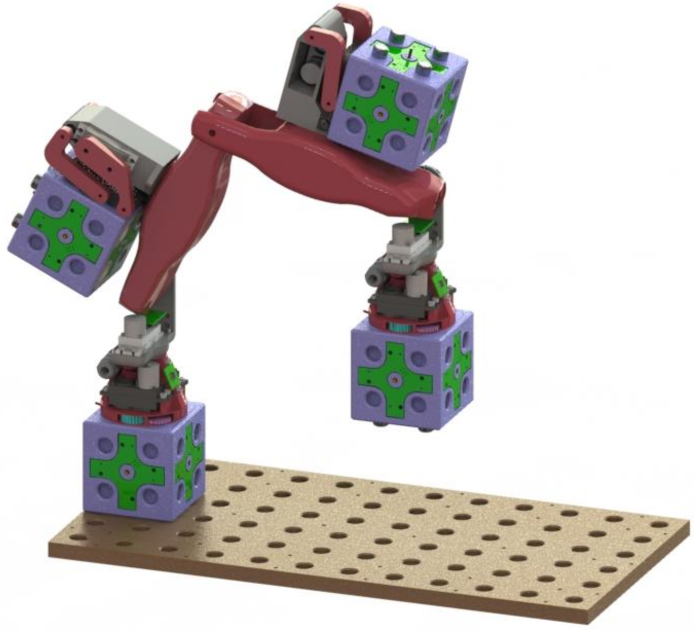
Structure Mating Design

- Single 4-40 bolt is used to
  - Provide attachment force between inchworm robot and the structure
  - Create strong connections between blocks to ensure that structures are stable
- Dowel pins are used to
  - Align the robot with its environment
  - Absorb shear stresses acting on robot-structure interface
- Large chamfers ensure consistent mating process



Expanded Robot Capabilities

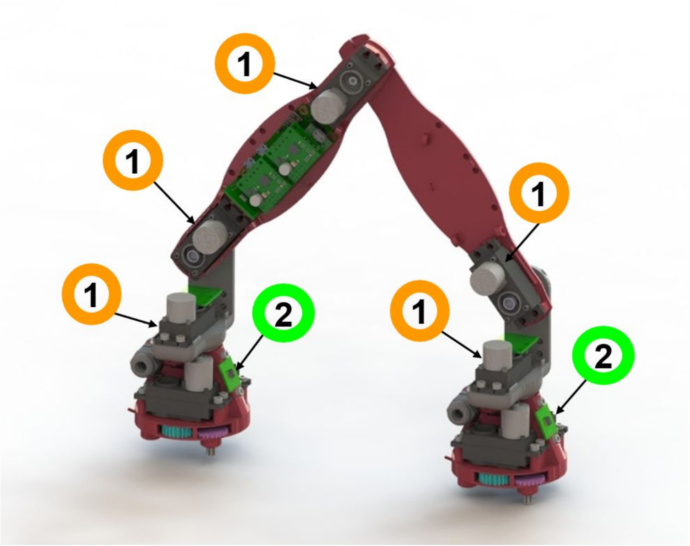
- Increased inchworm robot capabilities broadens the scope of building algorithms that can be tested
- Block storage mechanism
  - Enables robot to traverse structure with multiple blocks
- Modular end effector design
  - Current robot platform could become even more capable



Electrical Design

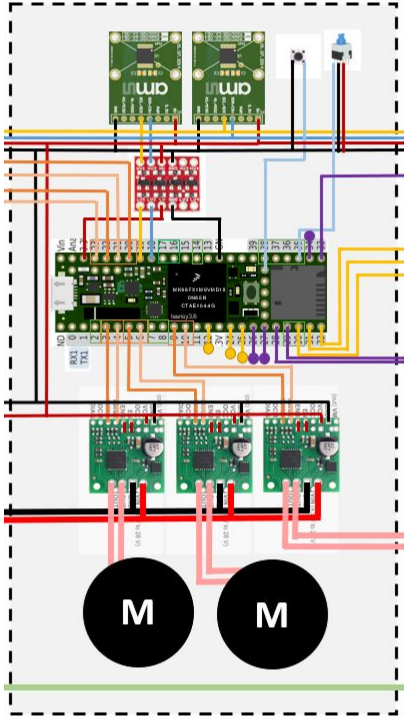
Electromechanical Components Overview

- Joints 1
  - Motor (30 kg)
  - Motor Controller (20 kHz PWM)
  - High Power BEC (9V)
  - Encoder (I2C, 14-bit High Resolution)
- Grippers 2
  - Motor (20 kg)
  - H-Bridge (6 V 2 A)
  - Hall Effect Sensor
  - Limit Switch
- Wiring
  - Wire Glands for strain relief between joints



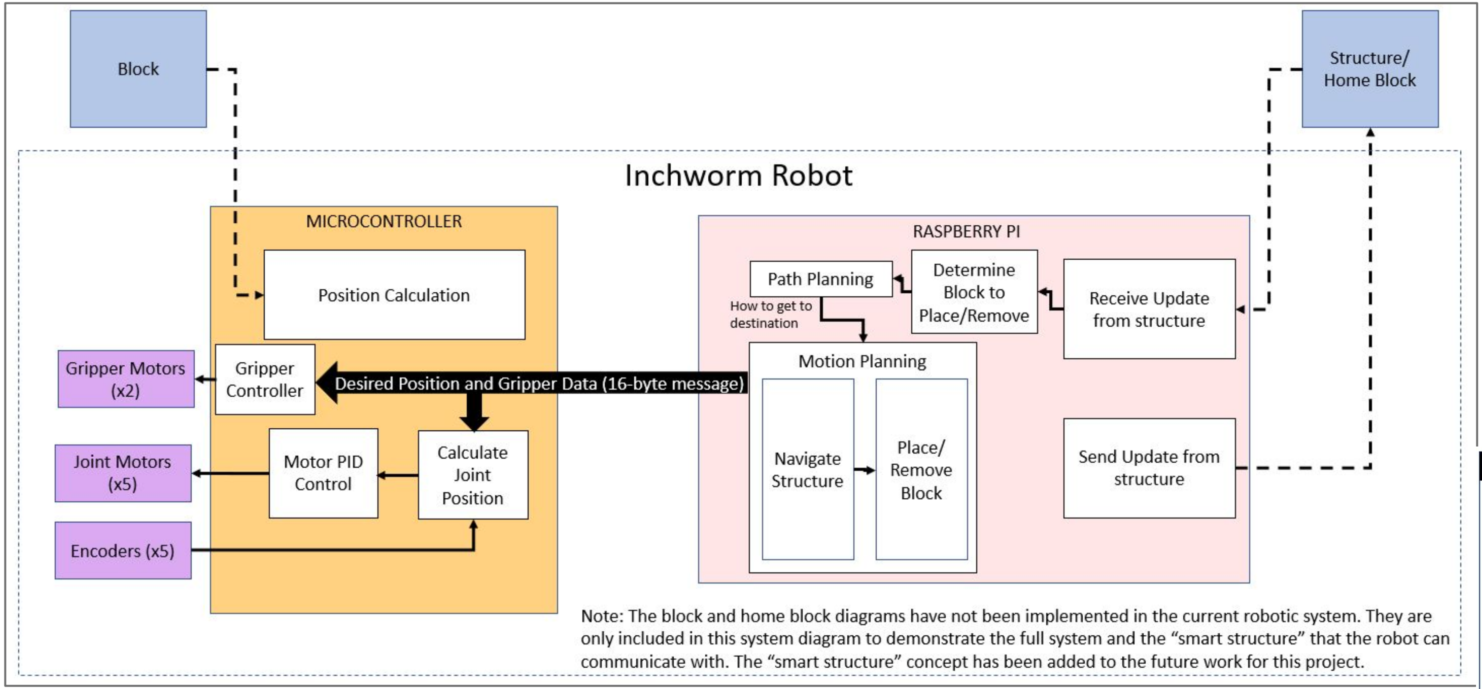
Low-Level Control System Hardware

- The Electronic Stack/Hub
  - Components
    - Teensy 3.6 Microcontroller (180 MHz ARM processor)
    - Raspberry Pi Zero W
  - Functionality
    - Allows for modularity
    - Easy to plug and unplug from robot
    - Robust and compact

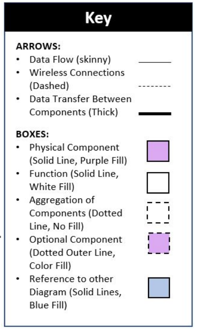


B-Link

High/Low-Level System Architecture



The architecture utilizes a small, on board computer for the high-level control, a microcontroller for the low-level controller, and USB serial for communication.



Low-Level Control System

- PID Controller
  - Each joint has its individual set of PID values
  - Dynamic: the PID values interchange based on the end effector attached to the structure
- Features
  - 5 msec control loop
  - Non-blocking gripper control
  - Manual PID tuning state

Communication Structure

- Kinematic control packet sent to controller over USB serial
- Packet received and parsed by low-level control system
- Packet Information:
  - Joint angles commands
  - Gripper commands

28-byte Data Control Packet

0000.00_ 0000.00_ 0000.00_ 0 0 0 0

Joint 0 (Θ) | Joint 1 (Θ) | Joint 2 (Θ) | Storage and Grippers

8-byte and 4-byte Decomposition

Joint: 0000.00_ (- or +; *Angles: 0-360.00*; *Unused*)

Grippers: 0 0 0 0 (*Select Storage*; *Storage State*; *Select Gripper*; *Gripper State*)

Select Gripper

Message (1 byte)	Action
0	Idle
1	Gripper 1
2	Gripper 2
3	Both Grippers
Default (>=4)	No Action

Gripper States

Message (1 byte)	Action
0	Idle
1	Engage
2	Disengage
Default(>=4)	Stop

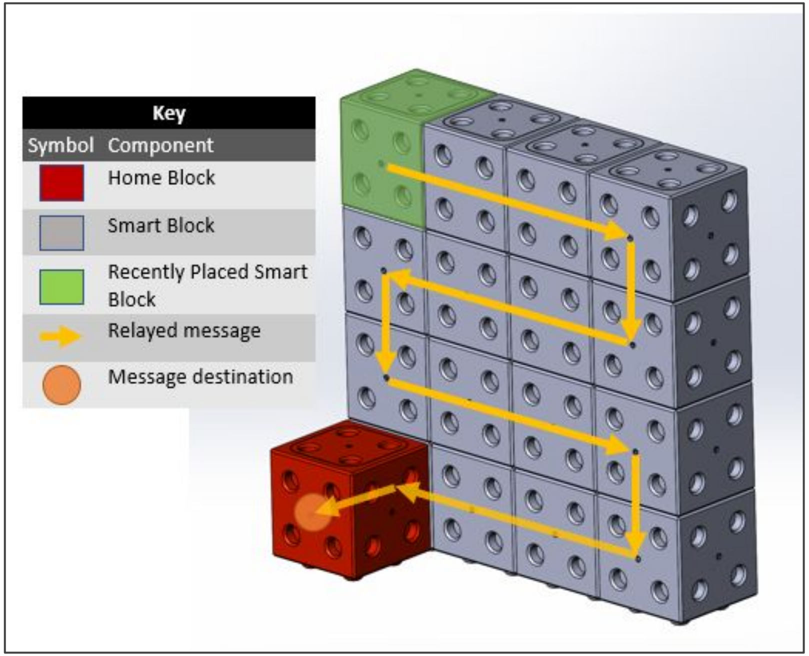
Inchworm Power Consumption

- Max power consumption is around 110 W with all components running at max power
- Power Source
  - 120 W wall power adapter
  - Unlimited power for testing robot
- Two High Power BECs per Robot
  - 9V with 10 A peak

Inchworm Robot Version 2	
Component	**Total Power (W)**
Teensy 3.6	0.264
Raspberry Pi Zero	0.612
Motors 30KG	109.2
Motor Controllers TB9051FTG	0.375
AS5048 Encoder	0.375
Motor 20KG	0.018
H-bridge TLE94003EPXUMA1	0.006
Hall Effect Sensor SS49E	0.06
Total Power (W)	110.91

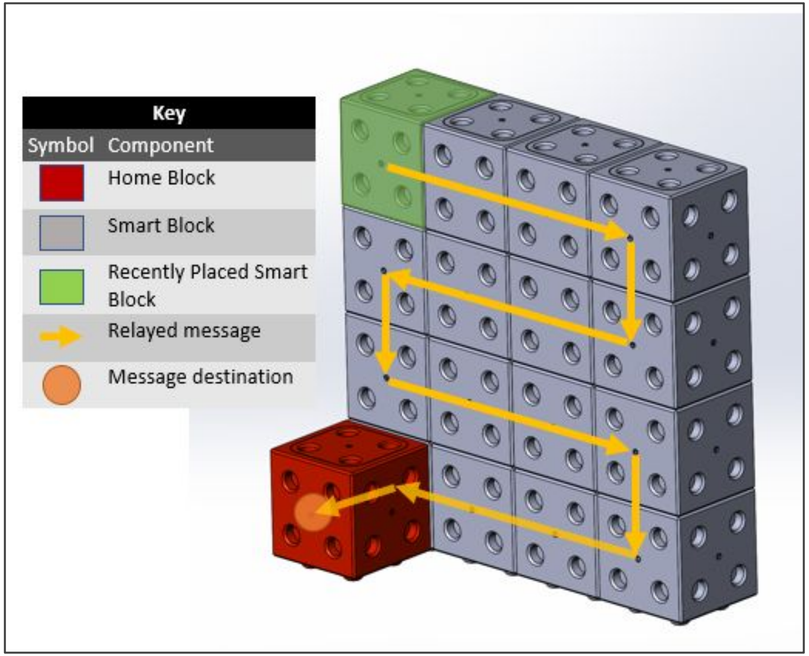
Smart Structure Concept

By making the 3D structure smart, it is able to communicate the structure’s configuration dynamically and verify an Inchworm’s position within the 3D structure.



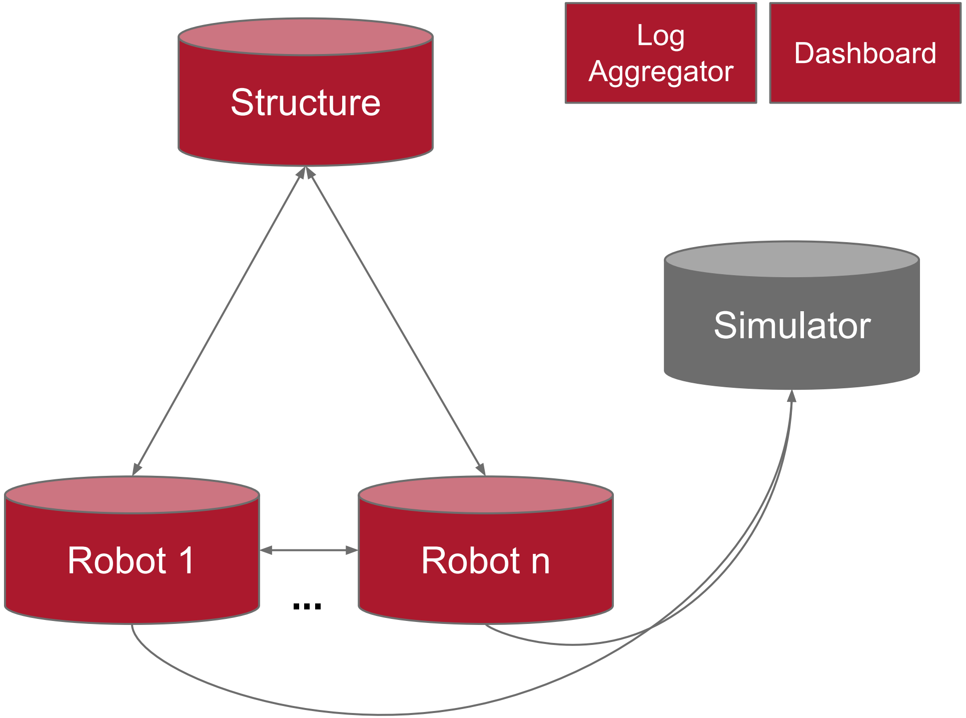
Smart Structure System

- Structure Status
  - Adding blocks dynamically updates the high level system
- Heartbeat Protocol
  - Allows system to identify if block is missing
- Robot Position
  - Robot can request position in respect to structure



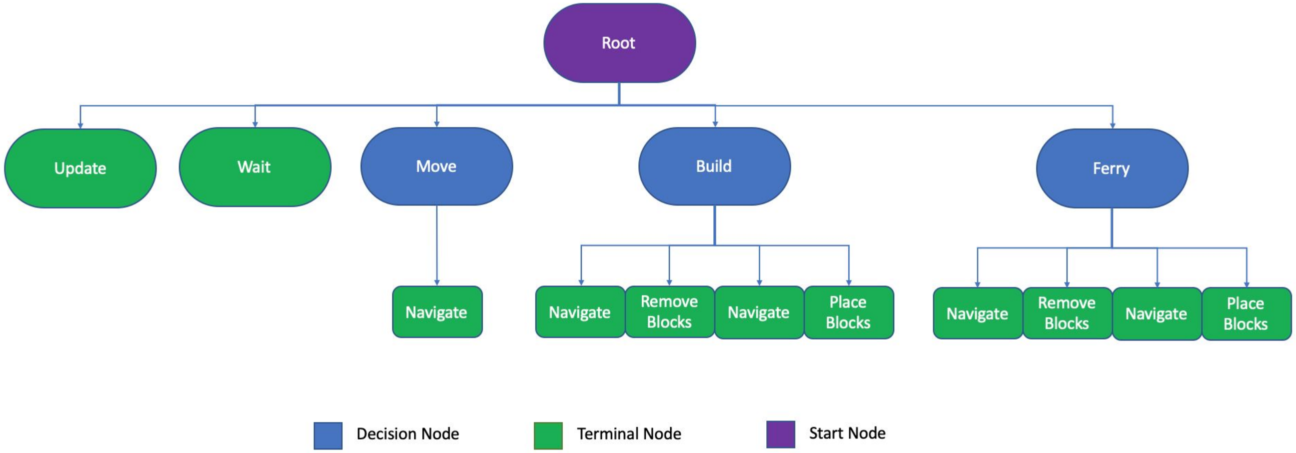
Software Design

Software Architecture



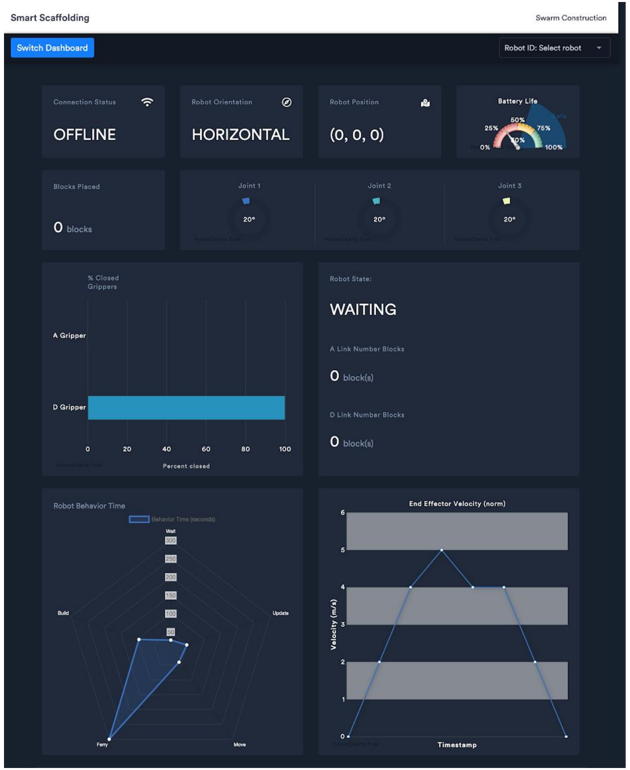
- The architecture involves software for the robots, a custom simulator, the structure, as well as a dashboard to monitor progress
- Each entity communicates with other entities over TCP

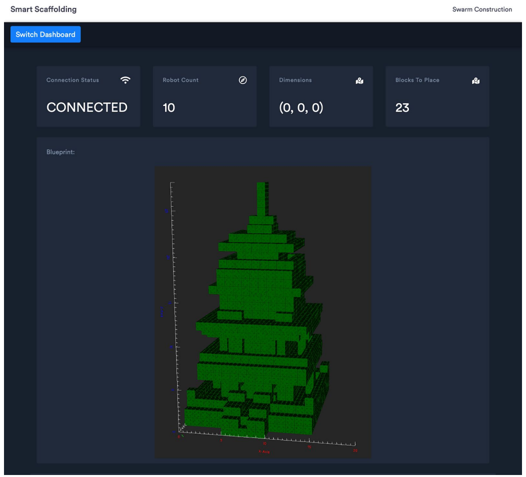
Robot Intelligence

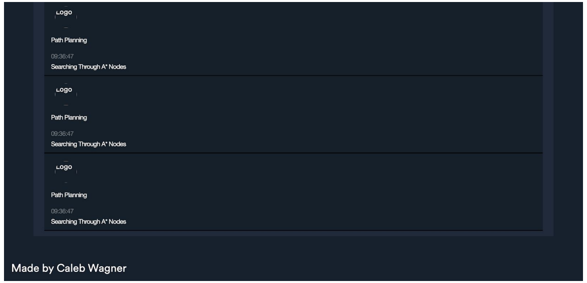


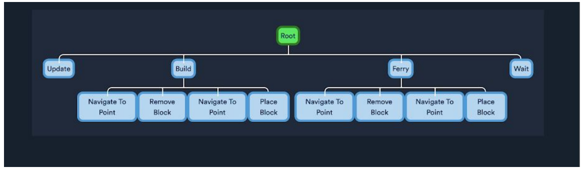
- The robots make decisions using a form of artificial intelligence called behavior trees
- Behaviors are defined for the robots, who then act according to the behavior tree

Dashboard



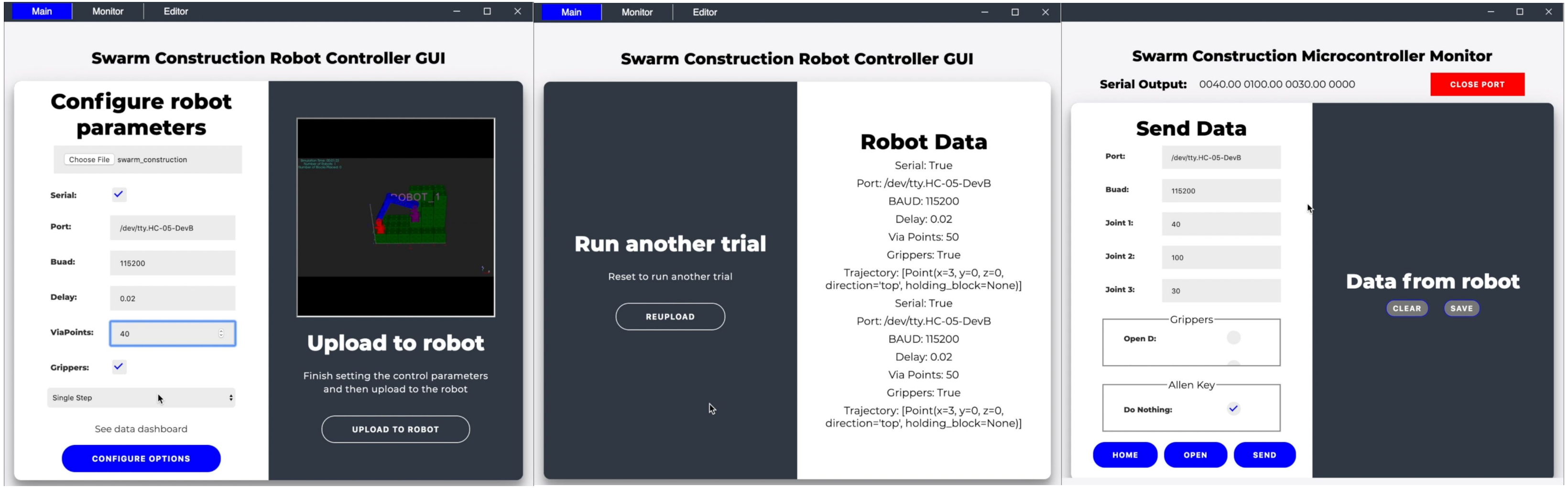






- A dashboard was developed so a user can monitor both the robot swarm and progress of construction

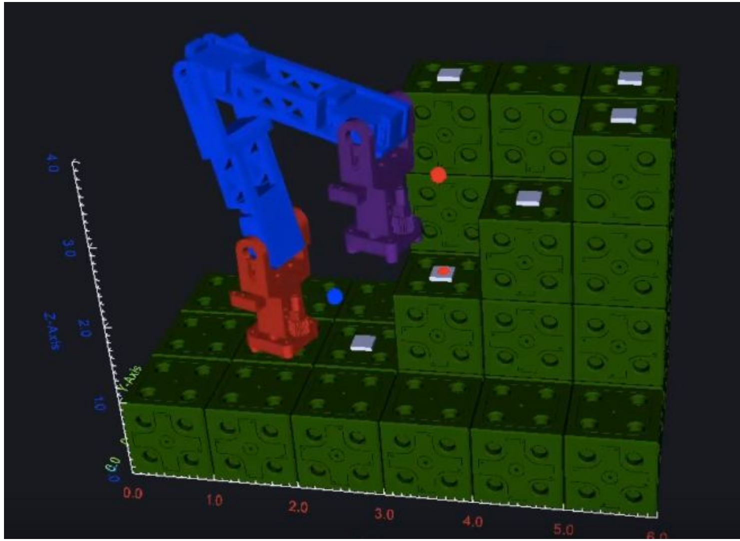
GUI



- Likewise, a GUI was developed to implement and debug and both high and low level control over the robots

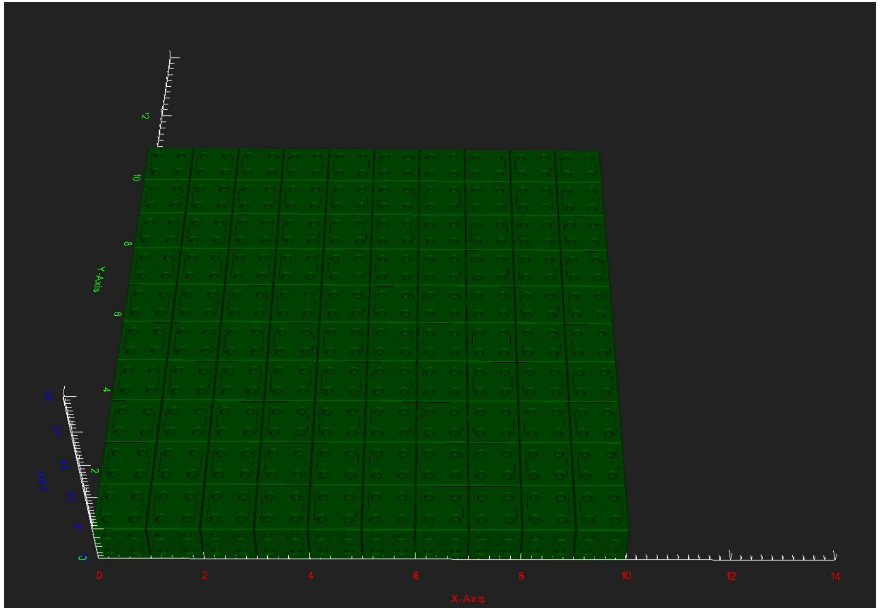
Robot Navigation (Face*)

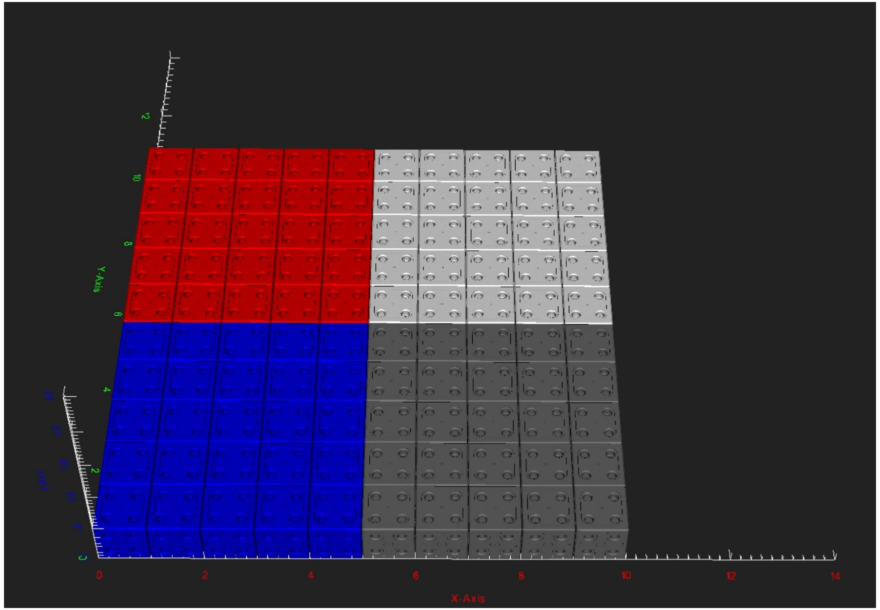
- To path plan for the robot, a variation of the A* algorithm was developed to allow the robot to traverse the different faces of blocks
- This algorithm, called Face*, searches through the faces of each block to find a suitable path for the robot



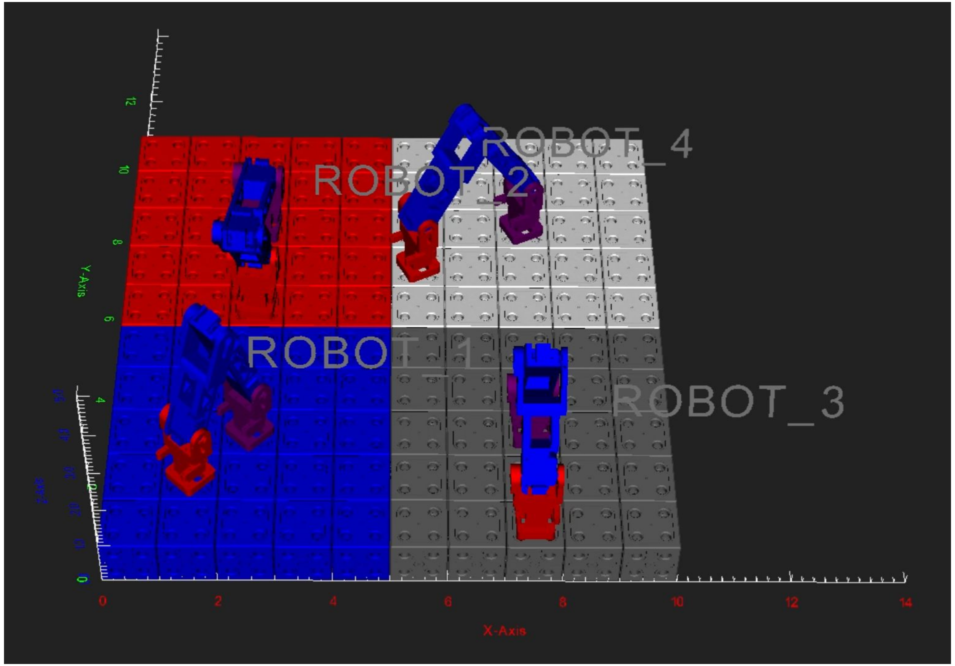
Collaborative Construction

- The building algorithm works by first dividing structures into regions, such as the four shown below



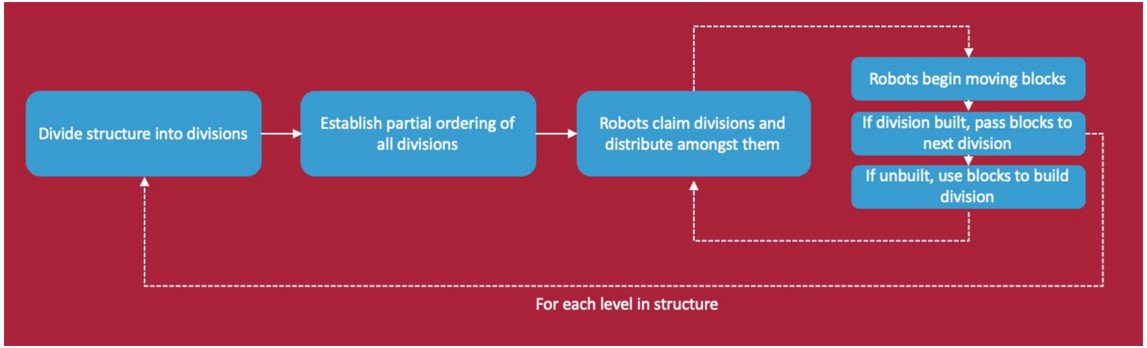


Collaborative Construction



- Next, the robots each claim a region as their own and distribute themselves
- They will monitor the construction of their claimed region

Collaborative Construction

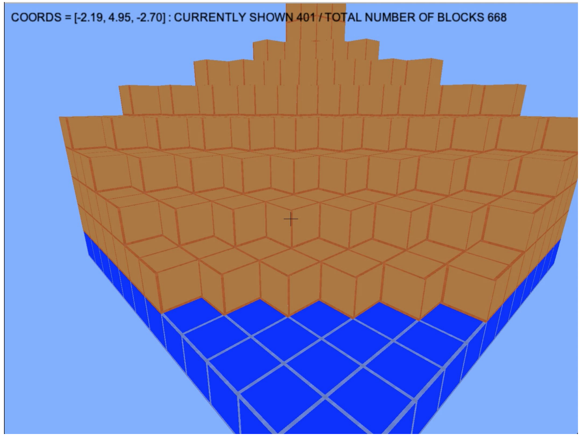


While in a region, robots will make decisions when they receive a block:

1. If the region is built, it will pass the block to other robots (known as ferrying)
2. If the region is not yet built, the robot will use the block to begin building that region

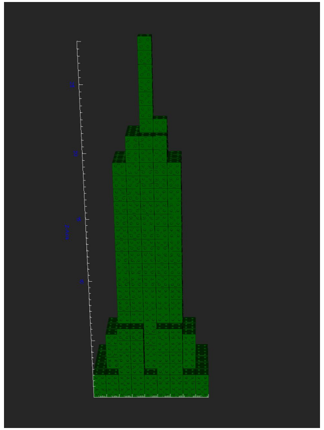
Construction Pipeline

1)



First, users can create a blueprint using our custom blueprint creator

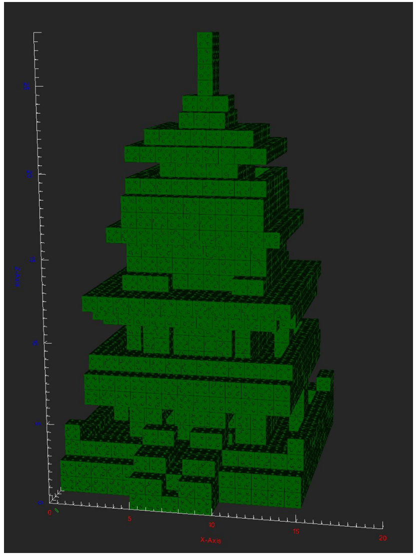
2)

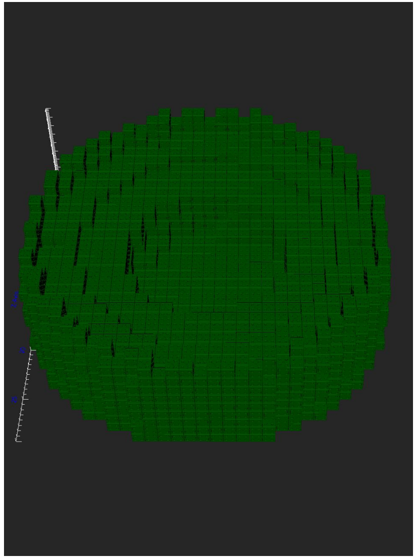


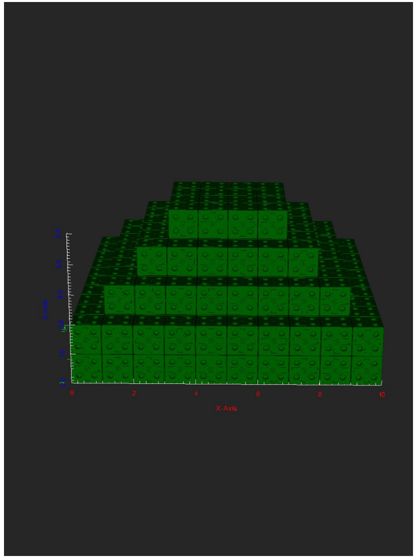
Next, the blueprint can be visualized in our custom simulator

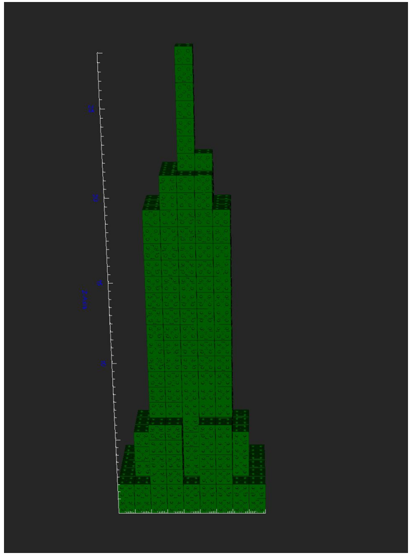
Collaborative Construction

3)





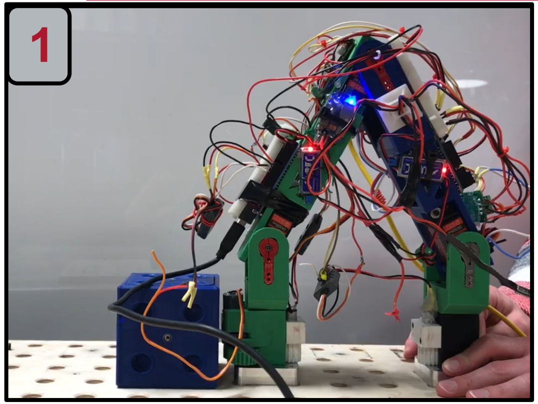


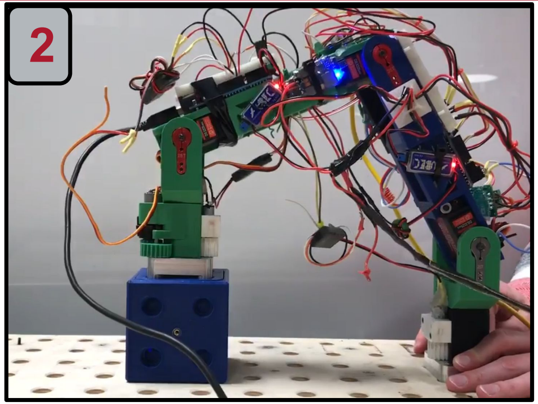


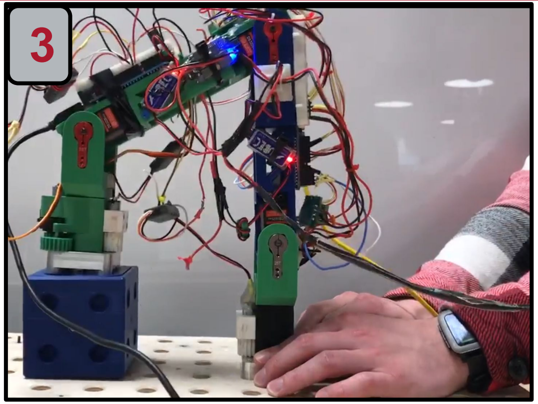
Finally, the building algorithm is used to build the given structure

Results

Prototype Inchworm Demonstration



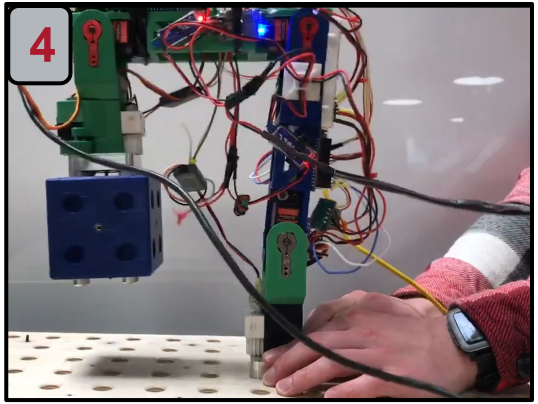


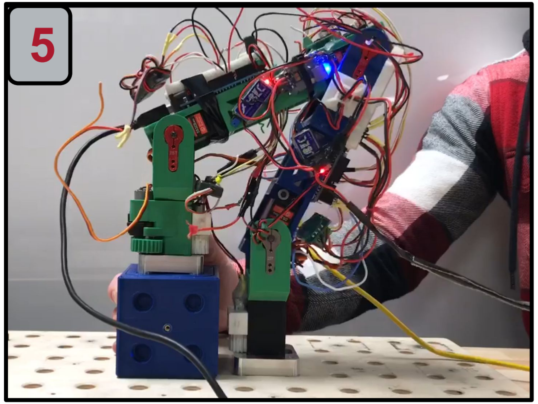


1: Robot is initialized with the goal of moving the block.

2: Robot moves end effector on top of block and attaches to it. Robot releases rear foot.

3: Robot uses block as support to move rear foot forwards. Robot attaches rear foot to the structure.

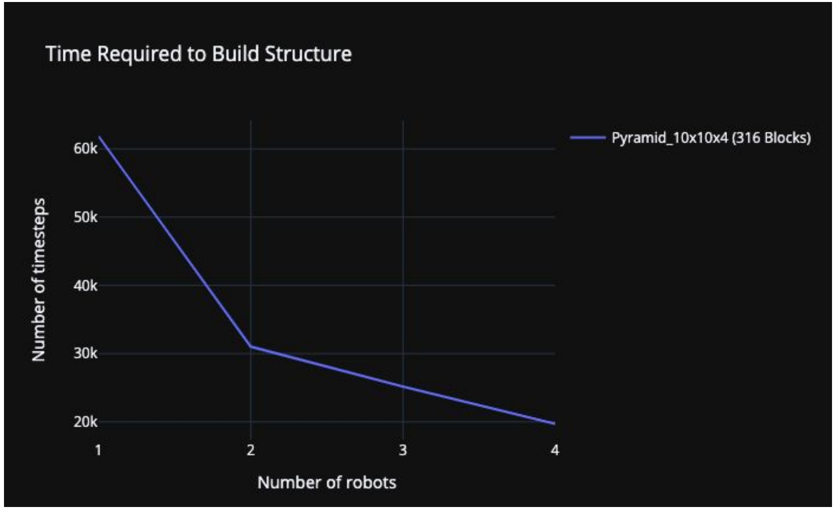


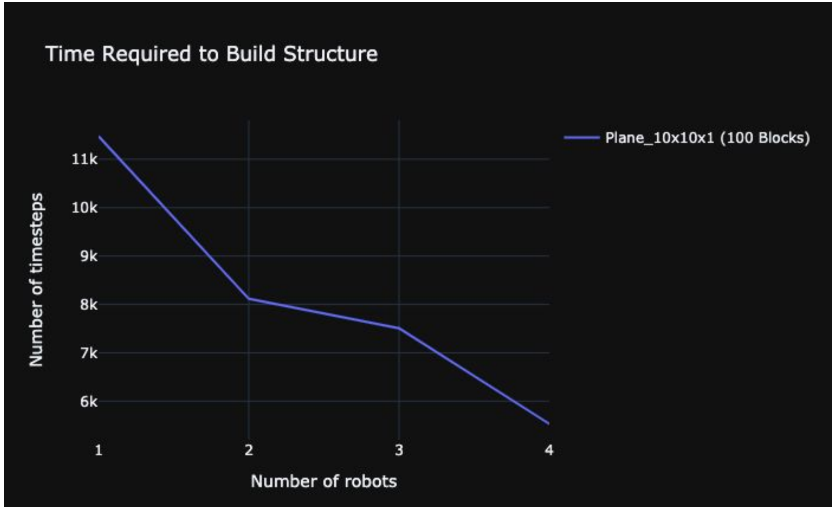


4: Block in midair.

5: Robot disengages block from the structure and moves it to the desired location.

Building Algorithm Evaluation





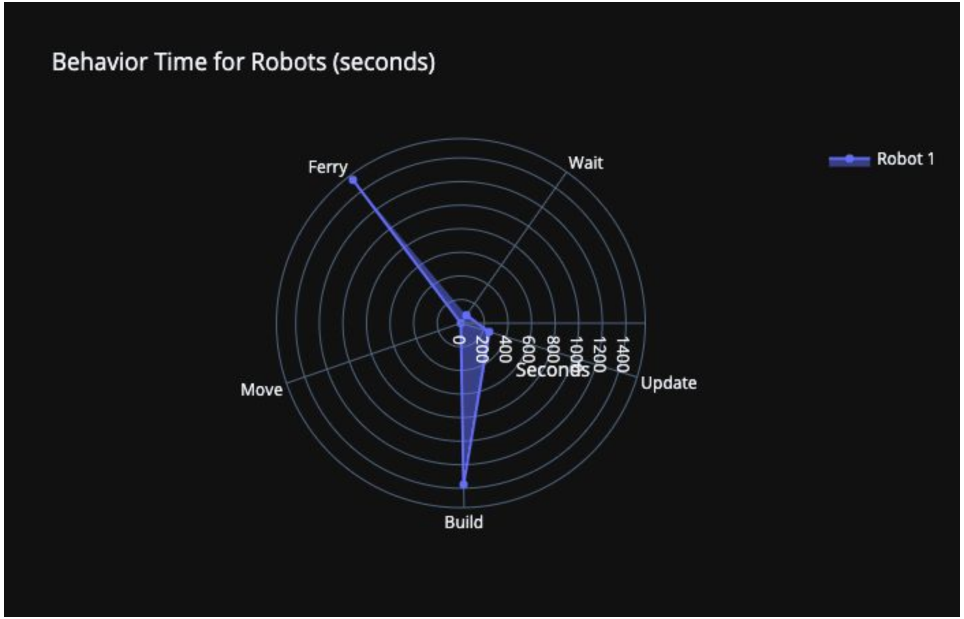
- The total time (timesteps) required to build different structures was measured
- As shown, adding more robots reduces the required time, such that using a swarm to build is beneficial

Robot Behavior Analysis

To measure the productivity of each robot in the swarm, the time each robot spent performing a particular behavior was recorded. The behaviors include:

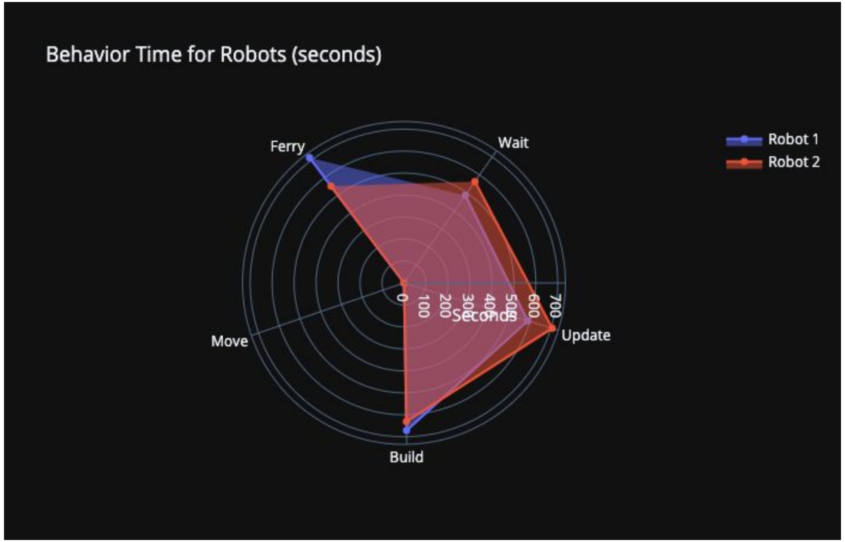
- **Waiting** *(robot does nothing)*
- **Ferrying** *(moving blocks around)*
- **Building** *(placing blocks to build)*
- **Updating** *(communicating with robots)*
- **Moving** *(told by other robots to move)*

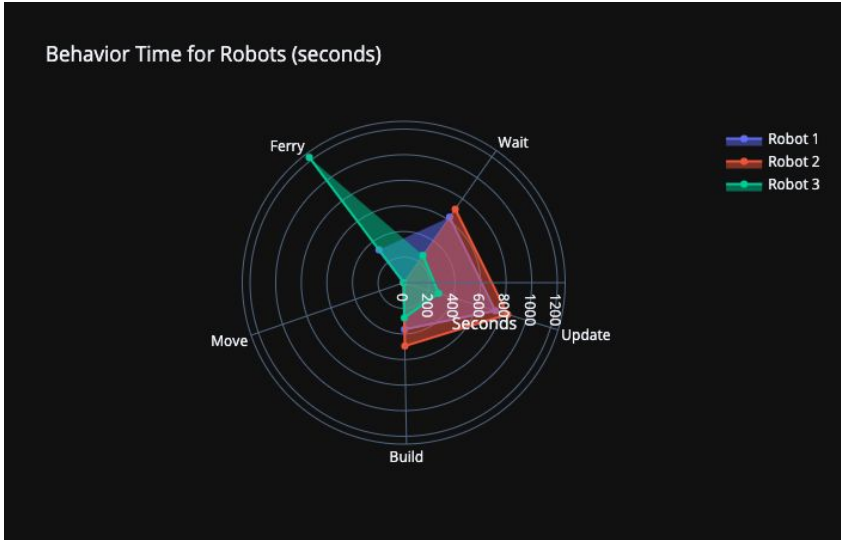
Robot Behavior Analysis



When only one robot is building, it spends most of its time either ferrying blocks (to itself) or building a division.

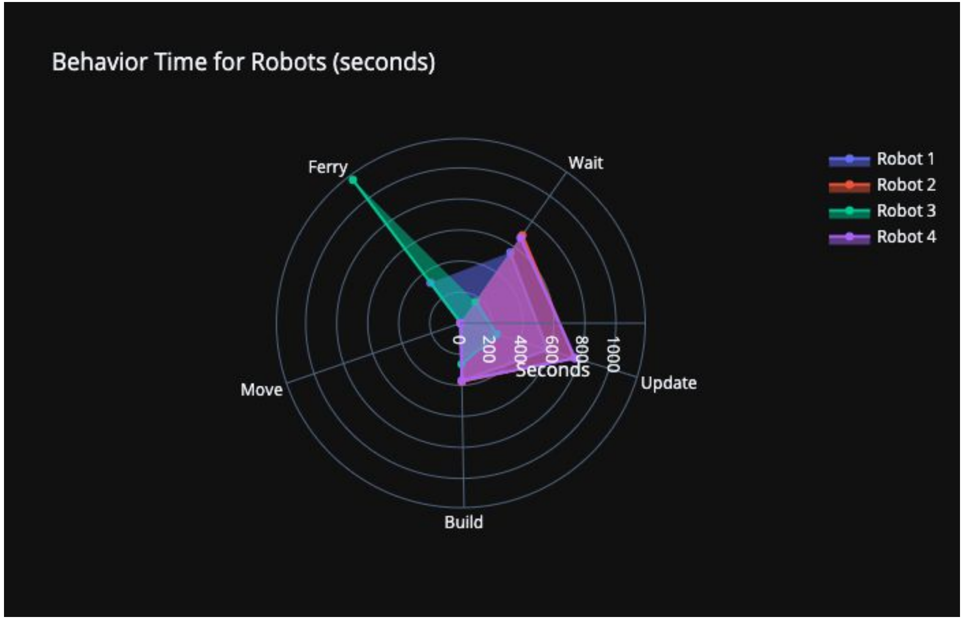
Robot Behavior Analysis





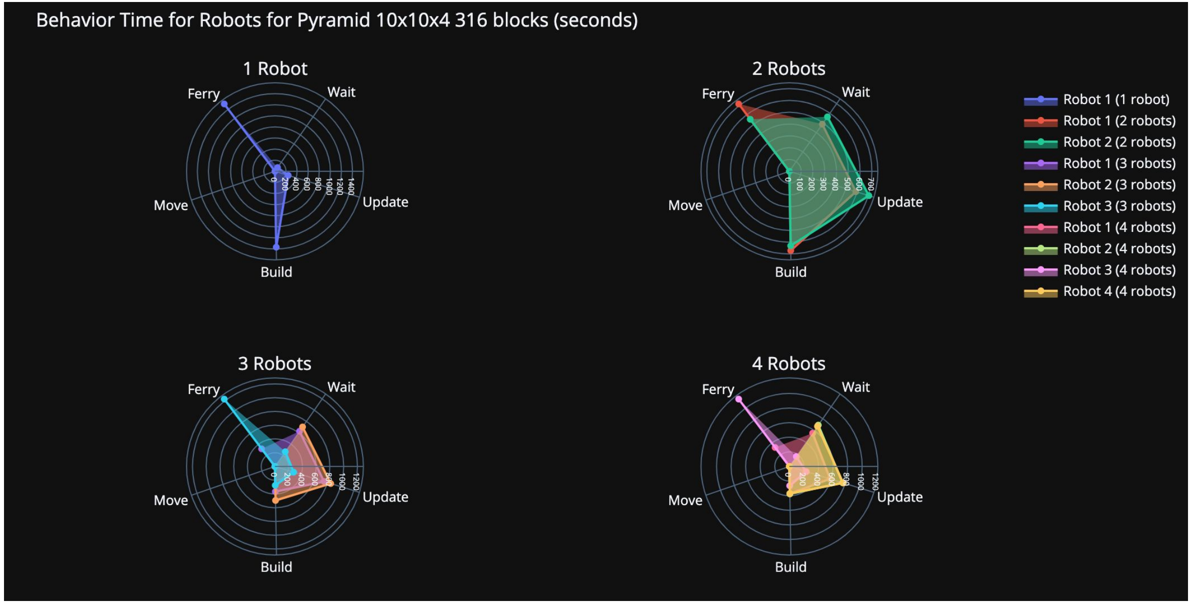
As more robots are added, robots spend time working on (specializing in) different tasks. Some robots spend more time ferrying, while others spend more time building.

Robot Behavior Analysis



Notice for four robots how the robots spend time working on different tasks, showing interesting characteristics of task specialization and can be used as an area for future research.

Robot Behavior Analysis



Here is a comparison of different sized swarms working to build a pyramid made of 316 blocks.

Conclusion

Conclusion

- We developed a robot (swarm) that has a high degree of mobility and functionality
  - We were able to demonstrate the capabilities of the robot especially in interacting with our blocks
- We developed a novel building algorithm that allows multiple robots to work collaboratively
  - We were able to conclusively show the benefit of and prove the correctness in using this building algorithm

Future Work

- **Building Algorithm:**
  - Expand the algorithm to factor in energy expenditure of the robots
  - Modify the algorithm to build supports for structures that are not globally connected
- **Robot:**
  - Manufacture a larger robot swarm
  - Add additional types of robots to create a more heterogeneous swarm
- **Smart Blocks:**
  - Develop cheaper means to manufacture smart blocks

Thank You

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