Robotic Assembly of Haptic Proxy Objects for Tangible Interaction and Virtual Reality

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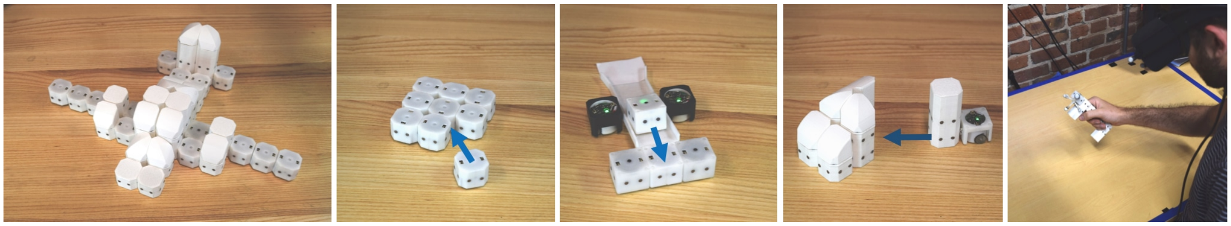


Figure 1. From left to right, a haptic proxy plane assembled by hand to demonstrate a potential complex shape; a square assembled using nine active blocks; two layers assemblies using active blocks; assembly of passive blocks of various shapes; user manipulating a haptic proxy object in a virtual reality application.

ABSTRACT

Passive haptic proxy objects allow for rich tangible interaction, and this is especially true in VR applications. However, this requires users to have many physical objects at hand. Our paper proposes robotic assembly at run-time of low-resolution haptic proxies for tangible interaction and virtual reality. These assembled physical proxy objects are composed of magnetically attached blocks which are assembled by a small multi robot system, specifically Zooids. We explore the design of the basic building blocks and illustrate two approaches to assembling physical proxies: using multi-robot systems to (1) self-assemble into structures and (2) assemble 2.5D structure with passive blocks of various heights. The success rate and completion time are evaluated for both approaches. Finally, we demonstrate the potential of assembled proxy objects for tangible interaction and virtual reality through a set of demonstrations.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords

Haptics; Passive Haptics; Haptic Proxy Objects; Tangible Virtual Reality; Robotic Assembly; Self-Assembly

ISS '17, October 17–20, 2017, Brighton, United Kingdom.

ACM ISBN 978-1-4503-4691-7/17/10...$15.00.
https://doi.org/10.1145/3132272.3134143

INTRODUCTION

Haptic feedback and tangible interaction form a key part of our experience in the physical world and allow us to dexterously manipulate objects and our environment. Leveraging users' innate ability to haptically perceive and manipulate 3D shapes is a core goal in both tangible user interface research as well as haptic virtual reality.

Researchers have investigated and developed various haptic technologies to try to enable this interaction. While many of them support certain aspects such as grasping [2, 5] or kinesthetic feedback [23], none has been able to emulate all sensations of touch. In addition, active haptic feedback often requires costly and complex hardware that encumbers the user. Physical props allow users to harness the sense of touch and natural manipulation proficiency by providing realistic kinesthetic and tactile haptic feedback, to support, for instance, complex data exploration [12, 17] or virtual object manipulation [10, 34]. The disadvantage of these rigid props is that they require users to either have many objects on hand or have inappropriately-shaped objects that might not match well with the virtual object being manipulated. Props can also be manufactured using digital fabrication and rapid prototyping technology such as 3D printers. Yet, current technology can take up to several hours to fabricate objects, and thus cannot provide users at run-time with haptic proxy objects for manipulation.

Another approach to enhance the tangible interaction with complex shapes is through the vision that Ivan Sutherland had for the Ultimate Display, "a room within which the computer can control the existence of matter" [36], or Hiroshi Ishii's vision of Radical Atoms in which "a new matter capable of changing form dynamically" is used for interaction [15].

Research on shape displays has made promising steps towards enabling Sutherland's and Ishii's vision. inFORM [6] is able to form any arbitrary 2.5D shape almost instantaneously. However, current shape displays are not well suited for many applications as these are grounded systems which users can only feel and touch but cannot pick up or manipulate freely. In addition, shape displays are complex and expensive.

We suggest another direction - self-assembly and robotic assembly of haptic proxy objects. Our proposed system is capable of providing both approaches. Using the Zooids robot system [19], it can both self-assemble and collaboratively construct physical objects. It uses magnetic attraction forces to either connect with other active blocks or fetch and unload passive blocks to assemble structures. We propose two methods to build physical proxies and evaluate these in terms of completion time and success rate. This serves as a guideline to decide which method to employ in different applications.

In summary, our contributions are:

- Self-assembly/collaborative construction system for tangible interaction and virtual reality.
- Two approaches to create physical proxy objects with magnetically attached blocks - active self-assembly and robotic assembly of passive blocks.
- Evaluations of both approaches to serve as a guideline for tangible and virtual reality applications.

BACKGROUND

Haptics for Interaction

To incorporate haptic touch in tangible interaction and virtual reality, many researchers have developed active haptic devices to create virtual forces, to support both tactile and kinesthetic haptic modalities [9]. Some have focused on a specific type of haptic sensation such as grasping [2, 5], kinesthesia [23], and tactile feedback [37], while others attempt to provide more complete haptic sensations by combining different actuators such as adding skin stretch device to a PHANTOM [23].

In contrast to active haptics, passive haptics aims at using existing objects to provide haptic feedback [12]. Passive haptics has been used for medical volumetric data browsing [12], scientific visualization [17], 3D modeling [34], interacting with user interface elements [21], and at a larger scale, representing entire rooms or spaces [13]. Passive haptic props can be generic or accurate physical models, fabricated by precision CNC machines [20]. However, the closer the alignment, the better the manipulation performance [18] and sense of presence [13]. Previous research on tangible user interfaces have explored using haptic proxy objects as handles for virtual content, but the phicons often do not fully match the represented objects [14]. Other systems have allowed developers to have a large class of physical props that can be appropriated for use in VR [10]. While some researchers have leveraged other users to reposition and assemble large scale haptic proxies [4], very few have explored robotic assembly of hand held proxy objects.

Programmable Matter

Although providing virtual forces can be an effective technique for many haptic applications, the current haptic devices are unable to provide all haptic sensations simultaneously. A way to overcome this is by physically building the virtual object. Ideally as mentioned by Ivan Sutherland, if a "computer can control the existence of matter" [36], then we can provide the exact haptic sensation. Two approaches to achieving this vision of programmable matter [8] and the "Ultimate Display" are Shape-Changing Interfaces and Self-reconfigurable Robots.

Shape-Changing Interfaces

One of the growing fields that realizes this concept of programmable matter is shape-changing interfaces [28]. They enable novel ways to serve both functional and hedonic purposes by changing factors like orientation, form, volume and texture. Examples include providing dynamic affordances through pin arrays [6], change between states using pneumatic actuation [38], and leverage smart materials such as shape memory alloy to manipulate surfaces [30]. Other researchers have begun to explore constructive assembly with shape changing blocks, such as the Changibles system which requires external manual assembly [32]. Others have used articulating and reconfigurable modular robots [31]. However, shape-changing interfaces have not been explored greatly in the domain of haptics for VR and few have explored self-assembly and assembly in this context.

Self-reconfigurable Robots

As mentioned by McNeely [24], "cellular robots" could be the solution to providing haptic feedback for VR by simulating the feel of an object through robots. Cellular robots, or self-reconfigurable robots, are capable of adapting their shapes and functions to different demands and environments by rearranging their mechanical connections. They can self-assemble both on-ground and off-ground, self-repair, easily scale up and down and even generate motion. Yim et al. used PolyBot, a system of self-reconfigurable robots to reach the goal of locomotion and manipulation of different objects [39]. Romanishin et al. designed M-blocks, a system of cubic modular robots driven by momentum that can connect with each other by magnetic force [29]. Other researchers have explored using active systems for latching, such as electro-permanent magnets, coupled with external vibration for placement and alignment [7]. While current research on self-reconfigurable robots are mainly focused on different mechanisms and applications such as search and rescue, space and medical devices, none to the author's best knowledge has looked into applying self-reconfigurable robots for tangible interaction in VR.

Collaborative Construction Robots

Robots are also capable of constructing physical objects. This approach, compared to self-assembly, requires fewer robots to build more complicated structures, albeit increasing construction time. For instance, TERMES [26] can build complex structures with only three robots, using a distributed algorithm. Different actuation technologies have also been used for collaborative construction: Lindsey et al. use quadrotors to build cubic structures [22], while Schoessler et al. utilize shape displays [33], and others use magnetically actuated microrobots [3]. Depending on the available resource, collaborative construction robots can be more suitable than self-reconfigurable robots.

CHALLENGES FOR ASSEMBLY SYSTEMS FOR HAPTICS

While the robotics research community has explored assembly of modular objects, their application to VR and HCI introduces new non-trivial challenges. Based on our own explorations and prototyping as well as earlier research [27, 30], we see the following challenges towards the creation of an ideal system:

Speed. Haptic proxy objects have to be available within reach as users are about to manipulate their virtual counterparts. The overall speed of the assembly process thus needs to allow uninterrupted and seamless interaction.

Spatial Resolution. Objects that can be encountered in VR are rich and diverse in shape, size and form. To provide realistic haptic cues, assemblies have to support resolutions that allow users to match virtual objects and haptic proxy objects with sufficient identifiable features.

Modularity. Assembly systems have to be usable in various contexts. To this end, haptic proxy objects should be able to be disassembled and utilize reusable elements, in order to keep the size of the system adapted to the usage.

Scalability. Assembly systems of haptic proxy objects have to be able to support this diversity without hindering overall performances. The number of elements in the assembly has to be able to range from a few to dozens.

Manipulability. Assembled haptic proxies should be able to be easily manipulated in 6 degrees of freedom. They should be ungrounded from any other surface or object.

Minimal external hardware. As intrinsic motivations for assembled haptic proxy objects include flexibility and transparency, assembly systems should not add complexity to the platform.

These characteristics depict an ideal assembly system to create haptic proxy objects. In this paper, we describe our first attempt to tackle these challenges using currently available technology at a relatively low cost, using simple robots and a simple connection strategy. We address some of these challenges in the limitation section.

IMPLEMENTATION

Our approach consists of two assembly strategies: an active method and a passive method. For both methods, the magnetic building blocks are actuated using small mobile robots. These are non-holonomic wheeled robots that can move freely on a 2D surface using a differential drive.

More specifically, we used Zooids [19] as a platform for our assembly system. Zooids can be controlled by a central server through a 2.4Ghz radio and report their position and orientation by using a high-speed DLP structured light projector for optical tracking. More details on their implementation can be found in [19].

Magnetic blocks

Users need to be able to pick up and manipulate the assembled structures. Blocks thus need to be able to attach to each other. Zooids offer only limited capabilities regarding the size and weight of the objects they can move. In order to minimize these two characteristics, we chose to use low-cost small permanent magnets (3.2mm×3.2mm×1.6mm), each weighing 0.1g. Eight magnets are sufficient for one block and we can easily modify Zooids to have an external shell with integrated magnets. The main limitation of this approach lies in the constant nature of the magnetic force. This lack of control implies that a block cannot be robotically disassembled and reconnected if mispositioned.

Others have used different actuated connection methods, including a latching system [25] or electromagnetic binding system [16]. Though these systems make the connection controllable, they have complex structures and require more space than the passive magnets design, thus reducing the spatial resolution of the assembly system. Those systems are also more expensive and require more power than permanent magnets.

Blocks for active method

For the active method, we designed the magnetic building blocks as external shells into which a robot can fit. As shown in Figure 2(a), the shape of the blocks are designed to be a 28mm × 28mm × 22mm cube with two magnets of opposite polarity on each side. This allows magnetic connection between any sides of any block.

In order to extend self-assemblies to 2-layer structures, we designed a ramp controlled by two robots, one on each side as shown in Figure 2(b). Rails on the sides of the ramp prevent robots from falling as they climb up the ramp.

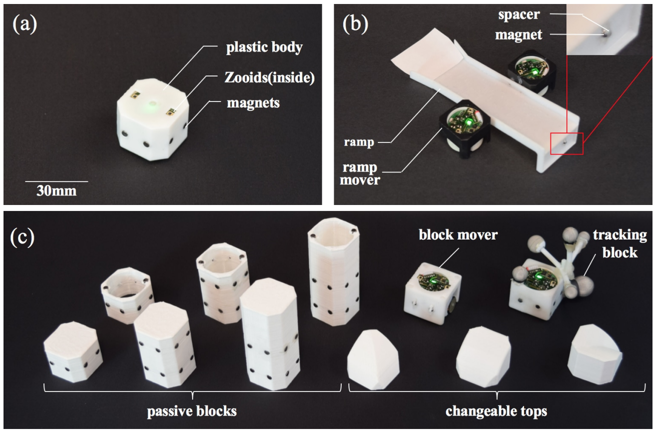


Figure 2. a) An active block consists of a shell containing a Zooid and magnets distributed around its surface to connect with other blocks. b) The ramp is actuated by two Zooids and allows active blocks to climb on top of each other. c) Passive blocks come in various shapes to allow to create more diverse assemblies.

Blocks for passive method

For the passive method, there are four elements of blocks, as shown in Figure 2(c): passive blocks, interchangeable tops, assembly robots, and a tracking robot. The passive blocks are 28mm × 28mm × *h*mm cubes. *h* represents the height of the passive blocks and includes value of {25.4mm, 2 × 25.4mm, 3 × 25.4mm}. The taller blocks require two layers of magnets, to provide stronger magnetic bonds with surrounding blocks and sustain the weight of the assembly. Two magnets placed on the top of some blocks allow to hold the interchangeable tops. To minimize the force required to move the passive blocks and the likelihood of unintentional block disconnection, the weight of passive blocks was reduced to 4-10 grams by hollowing them out. This is important to minimize the force needed to move the blocks.

We use assembly robots to move and assemble these passive blocks. One side of these robots has two ferromagnetic balls which bind to the magnets of the passive blocks. A plastic spacer is placed on top of each ball to increase the distance and thus limit the magnetic force. This allows the magnetic force to be strong enough to pick up the passive block, but also weak enough to be able to disconnect from passive blocks.

Unlike the active method, passive blocks do not contain robots and thus cannot track their position and orientation. Therefore, a tracking robot is necessary to support the localization of each passive structure in space. This tracking robot is equipped with retro reflective markers enabling localization using a motion capture system, specifically OptiTrack [1].

We designed three types of changeable tops: an outside corner, a fillet and an inside corner. These allow assembly of more detailed and consequently higher-fidelity shapes.

Active Method

Each block contains a robot enabling them to both move and track their position and orientation. With two magnets on each side, the blocks assemble, *i.e.* magnetically attach to each other, when positioned next to each other. We detail here how we compute the assembly sequence, how the blocks dock, and how the method can be extended for 2-layer structures.

Assembly Sequence

For each assembly method, a high level sequence planning enables avoidance of collisions between blocks, but also minimizes the overall assembly time. Moreover, in the case a block is assigned to a location we call a "narrow gap" in-between where two blocks are already positioned, the third block is more likely to be misaligned. Thus, our sequence planner tries to avoid these narrow gap situations.

Our assembly sequence starts from the center of the structure and rotates outwards in spiral. We divide the space into a square grid according to the size of a block. A target configuration (s) can be represented by a set of integer pairs (x, y) corresponding to the rasterized position. The output assembly sequence (o) is a list of integer pairs. The algorithm detailed below starts the assembly at point $(0,0)$. Lines 3 through 12 of the pseudocode go along the x and y axes alternately and check each position. If the position is included in the target configuration, it is queued in the output sequence. Finally, lines 13 and 14 change the direction and limit of checking to make it rotate outwards in spiral. Figure 3(left) illustrates this sequence planning strategy with nine blocks, where the number on the block and the arrow show the assembly order.

ACTIVE ASSEMBLY SEQUENCE(s)

```
1   $x_{limit}, y_{limit}, x_{dir}, y_{dir} = 1; x, y = 0$
2   while $size[s] > 0$
3       do for $i = 0, \ldots, x_{limit}$
4               do if $(x, y)$ in $s$
5                       do $o.queue((x, y))$
6                          $s.remove((x, y))$
7                   $x \leftarrow x + x_{dir}$
8          for $j = 0, \ldots, y_{limit}$
9               do if $(x, y)$ in $s$
10                      do $o.queue((x, y))$
11                         $s.remove((x, y))$
12                  $y \leftarrow y + y_{dir}$
13         $x_{limit} \leftarrow x_{limit} + 1, y_{limit} \leftarrow y_{limit} + 1$
14         $x_{dir} \leftarrow (-1)x_{dir}, y_{dir} \leftarrow (-1)y_{dir}$
```

Using this planning strategy, we can guarantee that there will only be two possible situations, a direct case (*i.e.* only one block out of four surrounding the target position before a new block is moved to the target) and a corner case (*i.e.* two blocks surrounding the target position), and that no narrow gap situation will occur.

At the beginning of the assembly, the active blocks surround the target structure and remain idle. The positions are assigned to minimize the total traveling distance of each block. Figure Figure 3(left) illustrates this, where the dotted-lined boxes are the idle positions and the hollow blue arrows are the final goals of each block.

Docking

The process for each block's assembly is shown in Figure 3(right). The block is first sent to the ready position, closer to the target position. If the block needs to be assem-

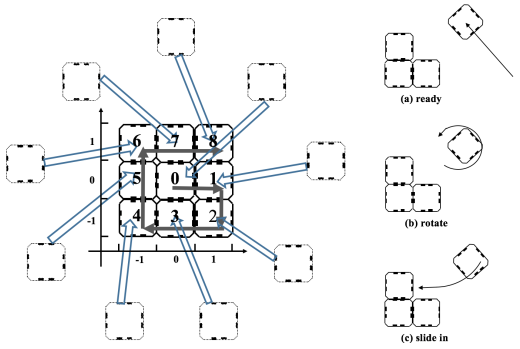


Figure 3. The active method starts the assembly at the center of the object and adds blocks by growing outwards (left). Each block adjust its orientation before docking to maximize the chances of success (right).

bled in a corner position, the ready position is set to be in diagonal of the target. The active block then adjust its orientation, and finally slides in to the target position to make sure it doesn't get stuck when assembled. The magnetic attraction forces help to align the final assembly, as the positional accuracy of the Zooids system is roughly 1cm.

Self-assembly of 2-layer structures

To assemble 2-layers structures, we use a row by row assembly sequence to minimize the distance that the ramp has to travel. After self-assembly of each row of the first layer, we determine whether a second layer is necessary. If so, we first move the ramp to the appropriate location, move an active block up the ramp and let it snap into place through magnetic connection, and finally remove the ramp. This process is repeated for each robot on the second layer. Moving the ramp around the assembled structure allows to minimize the distance active blocks have to travel on top of other blocks, as the uneven surface created by adjacent blocks hinders the robots' traction. Currently, the system only supports two layer structures, but one can imagine using larger ramps to build multi-layer structures.

Passive Method

Active blocks allow for assembly of the target structure quickly with a relatively simple control strategy. However, the active method has several shortcomings. Since each building block needs one integrated robot to move, the number of robots required for a given structure increases linearly with number of blocks in the target structure. Thus, we explore the assembly of passive blocks to build more complex structures, even with a limited number of robots.

Assembly Sequence

Unlike their active counterparts, passive blocks cannot move without external actuation. We use robots to fetch and move passive blocks from starting to target position.

Yet, the robot may fail to disconnect from the passive block, once added to the structure. In this case, the robot remains connected to the structure and waits for next passive block to be assembled. New additions of passive blocks can help the robot to disconnect, as the docking creates vibrations throughout the assembled structure.

Considering the challenges above, the assembly sequence for passive method organized on a 2D grid is designed as follows.

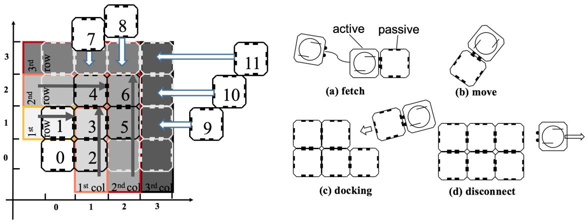


Figure 4. The passive method starts the assembly from the bottom left to the top right, line by line(left). The active robot block will fetch the passive block and push it to the target position(right).

We check the grid row and column alternately (in pseudocode Lines 3 to 6 and 8 to 11) and if the position is included by the target configuration set s, we queue it in the output sequence o. At Lines 7 and 12 we change the index of row and column to be checked.

PASSIVE ASSEMBLY SEQUENCE(s)

```
1   $x_{limit} = 0, y_{limit} = 0;$
2   while $size[s] > 0$
3       do for $y = 0, ..., y_{limit}$
4           do if $(x_{limit}, y)$ in $s$
5               do $o.queue((x_{limit}, y))$
6                   $s.remove((x_{limit}, y))$
7       $y_{limit} \leftarrow y_{limit} + 1$
8       for $x = 0, ..., x_{limit}$
9           do if $(x, y_{limit})$ in $s$
10              do $o.queue((x, y_{limit}))$
11                  $s.remove((x, y_{limit}))$
12      $x_{limit} \leftarrow x_{limit} + 1$
```

Figure 4 illustrates the passive method sequence planning, where numbers and arrows show the assembly order.

With this assembly sequence, we can guarantee that no narrow gap conditions will occur. Even if one robot is not successfully disconnected, it does not interfere with the rest of the assembling process as the robot does not occupy the space of the blocks in same row or column. This algorithm remains limited and cannot work for all complex structures and topologies. Yet, it works sufficiently well for the structures mentioned in this paper.

Fetching

Figure 4 illustrates all the steps for the passive method to fetch, load, move, assemble and disconnect from a single block.

Figure 4(a) shows how robots fetch and load the passive blocks. The robot first moves close to the block and changes its orientation so that the side with ferromagnetic balls faces the magnets on the block. The robot then drives slowly to the target and the magnetic force helps attract the passive block to the assembly robot. To make the connection stable during locomotion, robots always push the passive blocks. The spherical shape of the ferromagnetic balls allow the passive block to rotate when connected to the assembly robot (see Figure 5). The metal balls are higher than that of the magnets in the passive blocks. As shown in Figure 5, this causes the passive block to tilt such that only a single edge of it's base is in contact with the ground, thus lowering the friction forces.

Docking

With the assembly sequence described above, we only have two assembly conditions: the first one is when there is no new block in the new row or new column, we can simply let the robot move the block close to its target position, adjust the orientation and then push the block straight to the structure. For the second situation, the block needs to be assembled into a corner. Similarly to the active method, the strategy used here is push the block diagonally to prevent unintentional magnetic connection.

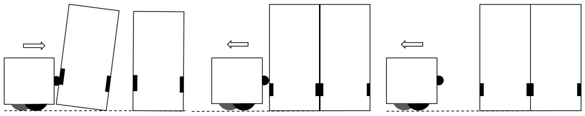


Figure 5. Docking magnets on passive blocks are slightly misaligned to facilitate transport and disconnection.

Disconnecting

Assembly robots need to be able to disconnect from the assembled structure to make space for the new incoming blocks. Two approaches are used to unload the passive blocks.

First, we leverage the difference in height of the ferromagnetic balls and the magnets. We carefully designed the height of the ferromagnetic balls on the active blocks, which are made to be slightly higher than the magnets on the passive blocks (see Figure 5). When the assembly robot fetches a passive block, the ferromagnetic ball allows the passive block to tilt and magnetically attach at an angle due to both the spherical shape and the difference in height, as shown in Figure5. However, when the passive block approaches near another passive block in the target structure, the relatively stronger force between the magnets in the passive blocks allows the robot to unload and disengage.

The second approach utilizes the vibration generated when another block is docked to the same structure. This vibration allows robots that were previously unsuccessful in unloading to unload and disengage. Even with both of these approaches, the robots are sometimes unsuccessful in unloading which leads to a failure as discussed in the evaluation section.

VR Setup

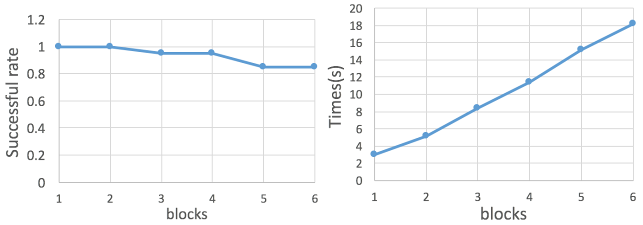
We use the Oculus Rift for the Virtual Reality (VR) system. In order to let the user manipulate and interact with the assembled blocks, we need to track the position and orientation of the assembled structure in 3D. The projector-based tracking used Zooids only provides 2D position and orientation, and thus is suitable only for assembly but not for 3D interaction with the assembled structure. We use an Opti-track system [1] to get 3D position and orientation of the tracking robot(block). Since we know the tracking block's relative position in the assembled structure, the system can then automatically calculate the overall object's center. All the scenes for different use cases are implemented in Unity.

TECHNICAL EVALUATION

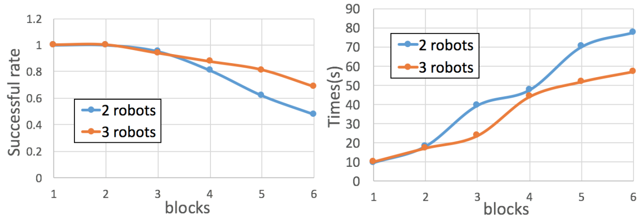
To evaluate and compare both the active and passive methods, we measured the completion time and success rate to assemble the same target structure, a 2×3 rectangle. All the robots and passive blocks were lined up in the corner of the working area, 0.5m away from the position where the structure is assembled. All the tests were completely automated and did not involve any user intervention once started.

Technical Evaluation for the active method

We recorded the completion time and success rate for each block for an assembly sequence. We repeated the assembly 21 times and reported the results in Figure 6. According to Figure 6a, the success rate remains 100% for the first two robots and decreases with additional target blocks. The final success rate is 85% for 6 blocks. The main reasons for failure are that the blocks get stuck or are assembled at an incorrect position, as shown in Figure 7.



(a) Success rate for active (b) Completion times for active



(c) Success rate for passive (d) Completion times for passive

Figure 6. Technical evaluation results for the active method and passive method

Prepare ramp	Climb ramp	Remove ramp	Total time (s)
7.7 (4.4)	12.3 (12.5)	4.4 (3.7)	24.4 (14.5)

Table 1. Mean completion time with standard deviation for each stacking.

The completion time is linearly proportional to the number of blocks (see Figure 6b). The average time for assembling one block is approximately 3 seconds.

We evaluated the success rate and completion time breakdown for 2-layer structures. We recorded the time for each new block stacked, and identified failure sources. Out of 36 stacking trials, 16 were successful (44%).

The completion time for the three steps of stacking (prepare, climb, and remove ramp) were measured and are reported in Table 1. Climbing up the ramp had the largest mean completion time followed by preparing the ramp and removing the ramp. There is a large standard deviation for the completion time when climbing up the ramp. This is due to three trials in which the robot was stuck at the bottom of the ramp for a long time (>20 seconds), but eventually managed to climb up the ramp. Out of the 20 failed trials, 75% were due to ramp misalignment when preparing the ramp, and 25% were due to the robot getting stuck while climbing up the ramp. The success rate could be improved by first enhancing the control of the ramp in order to minimize the ramp misalignment, but also by improving control of the robots as they climb.

Technical Evaluation for the passive method

We used the same method, assembling a 2×3 rectangle target shape, to evaluate the passive method. We conducted the technical evaluation with two and three active robots to see the effect of using different numbers of robots. As shown in Figure 6c, the final success rate for the passive method for 6 blocks with 3 robots is 68% and 48% with 2 robots. The main failure reasons are shown in Figure 7.

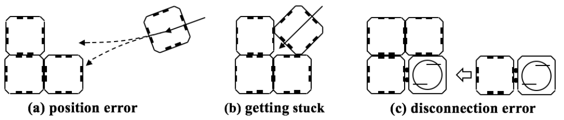


Figure 7. Main reasons for assembly failure. (a) and (b) both happen for active and passive methods, while (c) happens only for passive method.

1. The passive block is docked at an incorrect position, mainly because of inaccuracies in the robots' position tracking and control.

2. The blocks get stuck when it is pushed to a corner.

3. Robots fail to disconnect from the assembled structure, causing the assembly process to stop.

The technical evaluation results demonstrate that a higher number of robots leads to a higher success rate. Indeed, the probability that all the robots fail to disconnect decreases as the number of robots increases. Using three robots for instance, two robots can dock passive blocks and generate vibrations, helping the robot disconnect as it failed to unload after docking.

Figure 6d shows the assembly time for the passive method. Measurements reveal a non-linear relationship between time and number of blocks. The assembly process is done turn by turn, as robots fetch the passive blocks together (to avoid collisions), assemble them one by one and repeat this operation.

The robots then require a given amount of time to fetch new blocks at the end of each turn, thus increasing

at the end of each turn, it may take some time for the robots to fetch the block, thus making the time curve jump at the end of each turn.

For this reason, we can see that the more robots are used the faster assembly process can be. Using our current implementation, the results demonstrate completion times decrease as the number of robots increases. Specifically, the completion time drops from 12.8 to 9.6 seconds when three robots is used instead of two.

The evaluation shows that the assembly time for a single block using the passive method is 3 to 4 times longer than that using the active method. However if we look at the time spent on either getting the blocks (fetch and move) or assembling the blocks (dock and disconnect), we can see that getting the blocks takes 20.5 seconds while assembling the blocks takes 2.7 seconds. Using an algorithm that could avoid all the possible collision and optimize the assembly process, *e.g.* by preparing a block for docking while a block is being assembled, the total time for this ideal passive method would then be $(20.5+2.7x)$ seconds, where x is the number of blocks in the structure. In this case, the passive method can have a similar speed to the active method.

USE CASES

Shape Display

Using the self-assembly system, we can render different shapes with physical proxy objects. Figure 8 shows two examples of how we can interact with virtual objects in VR by manipulating the proxy objects. As a user moves their fingers along the virtual object's surface or grabs it, they can feel and sense the shape and weight of the virtual object albeit in low resolution.

The system can potentially render highly complex objects, as shown in Figure 1, using blocks of various heights. Due to the current low success rate for such complex structures with many blocks, we manually assembled this example object for demonstration.

Self-configurable Interface

While the self-assembly system can be used to construct and display different shapes and structures, it can also be used as a self-configurable interface, especially in VR. It can build physical proxy interface elements, allowing users to freely touch and feel the virtual object proxy. Users can also manipulate the assembled object in the virtual scene using it as an input device. Based on the application, our self-assembly system can construct different shapes and structures for interaction and we describe several example applications.

3D Virtual Drawing

For a 3D virtual drawing application, the self-assembly system constructs a pen-like shape as shown in Figure 9 for users to hold and manipulate. The physical proxy allows more natural interaction for users. The path of the proxy is tracked such that the virtual pen and its trajectory can be rendered accordingly in the virtual environment.

Interface with Orientation Tracking

In a virtual target practice application, the robots assemble a gun proxy for more immersive VR experience. The system tracks both the position and the orientation of the gun proxy allowing users to freely manipulate the proxy and accurately aim and shoot as shown in Figure 10.

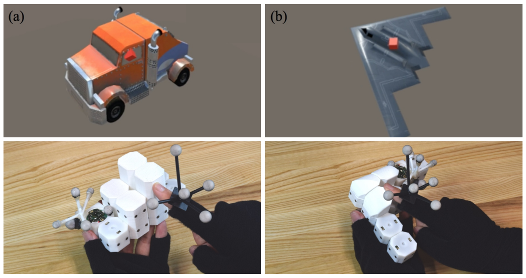


Figure 8. Assembled haptic proxy objects allow user to physically manipulate and interact with various virtual objects.

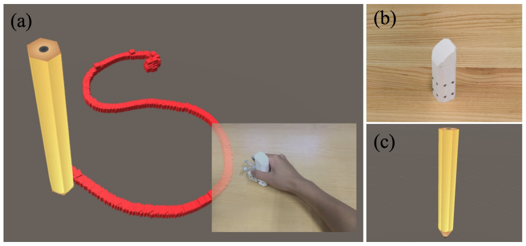


Figure 9. One can draw in the virtual world by manipulating an assembled pen proxy.

Interface with Virtual Switch
In addition to the six degrees of freedom in a single rigid body, we can add additional degree of freedom by adding more rigid bodies that connect to the assembled proxy. In this application, we connect an interchangeable top with reflective markers on top of the assembled structure through two magnets as shown in Figure 11. Users can disconnect one of the two magnets by pushing on one side of the top. The system can detect this rotation and use it as an additional input. In this application, it triggers the light saber to activate the laser as shown in Figure 11. The laser can be deactivated by pushing the top back to its original place.

Interface with Position Mapping
For all the applications described above, the position of virtual object is mapped exactly to that of the proxy. However in some application, the virtual object may have some constraints in its movement. Even though we can not provide those constraints in the real world, we can map the physical proxy to the virtual object such that it obeys the constraints in virtual world. As shown in Figure 12, the user grabs the handle to control the illumination of the lamp. The virtual handle can only be moved in one direction on the plane, while the real assembled proxy can be moved freely. Here we can simply read the movement of proxy only in the corresponding direction and render the virtual object accordingly.

LIMITATIONS AND FUTURE WORK

Assembly Success Rate - Our current implementation has a significant error rate especially with the passive assembly method, which limits the ability for the system to assemble complex structures with many blocks. This is due to mainly two sources - positional accuracy of our robot platform and issues with disconnection. The first could be improved with a better robot platform that has more torque and higher tracking accuracy. The second issue could be addressed by better docking and disconnecting methods between blocks. Permanent magnets could be replaced by electro-permanent magnets to increase disconnection reliability and allow for robots to reposition in case they dock in the wrong position.

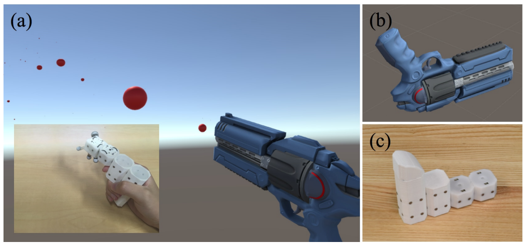


Figure 10. Tracking the orientation of this assembled proxy gun allows users to aim and shoot accurately.

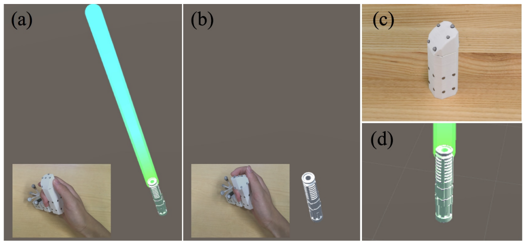


Figure 11. The assembled proxy light-saber includes a secondary marker. Flicking this top marker allows to open and close the light-saber.

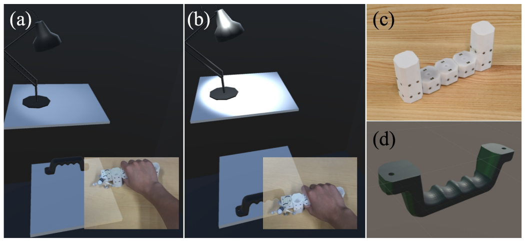


Figure 12. Moving the assembled proxy switch allows to control the intensity of the light in the virtual world.

Speed - While faster than 3D printing, our current system takes a significant amount of time to even assemble simple proxy objects. Multiple robots and parallel assembly as well as better planning and scheduling algorithms could improve assembly time. Finally, faster robots could obviously improve the speed of assembly, though it is likely to also reduce positional accuracy, and thus may not reduce overall completion time.

Spatial Resolution - It has been shown that resolutions of 2-3mm are needed to accurately represent an object for haptic shape perception [35]. Our blocks are roughly 28mm wide. Smaller passive blocks could enable this, but would take longer to assemble given the increased number of blocks. For the active condition, it is difficult to build much smaller multi robot systems, often due to the size of available actuators and power sources. Moving to wireless power distribution and other actuation technologies, piezo or magnetic, could further reduce the size. In future work, we could also combine assembled haptic proxies with visio-haptic illusions for higher perceived resolution.

3D Assembly - With our current system we have only demonstrated assembly of 2 layer structures without overhangs. With magnetic assembly of passive blocks it is possible to imagine assembly of structures with overhangs (the magnets could allow blocks to overhang). However, the ramp method is clearly limited. More advanced and specifically designed robots could be created to better deliver blocks to higher levels, such as miniature fork lifts. Or structures could be assembled in a single layer and then raised up, using a jack or other means, allowing for blocks to be assembled underneath and the whole process repeated to build more layers.

Optimal Voxelization - Currently, our models are hard coded. In future work, better optimization techniques can be used to find the optimal position and orientation of blocks to represent a given high resolution model.

Disassembly - Because our system uses permanent magnets for assembly, it requires users to manually disassemble the proxy objects for reuse. Higher torque motors or an unlatching mechanism could enable the active blocks to automatically disassemble. The passive blocks could use electro-permanent magnets [7] to disassemble, but this would increase the cost of the passive blocks substantially. Another approach would be to move the assembled structure to a certain area where a custom disassembly system could disassemble it using more powerful actuators and shear motions.

Locomotion of assembled structures - It would be beneficial to move the assembled structures after they have been assembled in a number of VR contexts, such as remote collaboration or any type of animated object. For the active blocks, this would require more complex and potentially distributed control strategies for locomotion. For the passive method, stronger robots would be needed to manipulate the assembled structure.

External Digital Assembly - Self-assembly and robotic assembly using small mobile robots has great promise in the future, but has many limitations as described in this section. We believe, in the short term it may be preferential to explore digital assembly of similar structures using an external platform. Researchers in computational fabrication and digital fabrication have begun to explore digital assembly [11]. We imagine these types of printers could quickly generate low resolution structure much more quickly and efficiently than either 3D printers or robotic assembly methods described here.

CONCLUSION

In this paper we introduced a system for robotic assembly of haptic proxy objects. We described two methods for assembling magnetically attached blocks - self assembly with active blocks and robotic assembly of passive blocks. While our technical evaluation highlighted a number of challenges with our current system, mostly positional accuracy of robot control, we believe that this demonstrates the possibility of robotic assembly for tangible interaction and virtual reality. Our demonstrations, while simple, already highlight some meaningful use cases with low resolution assembled proxy objects. Our hope is that advances in robotics and digital assembly will enable the just-in-time assembly of proxy objects at a much faster rate.

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