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

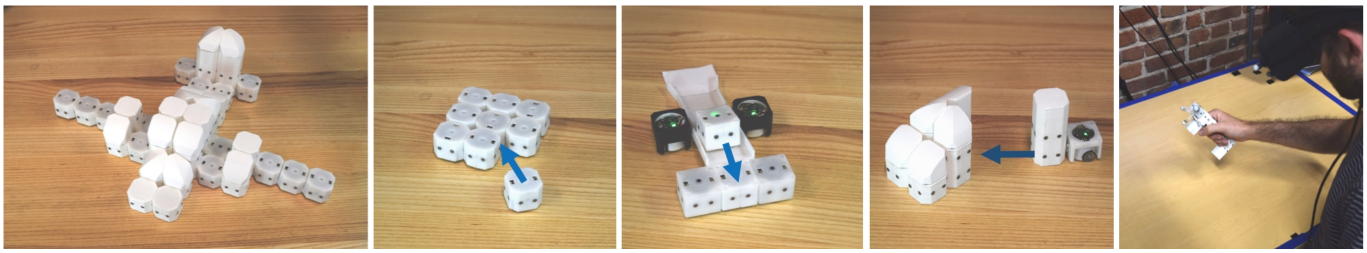

Figure 1: From left to right, a haptic proxy plane assembled by hand to demonstrate potential complex shape; a square assembled using nine active blocks, two layers assemblies using active blocks; assembly of passive blocks of various shapes; user manipulating a haptic proxy object in a virtual reality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

ABSTRACT

Passive haptic proxy objects allow for rich haptic interaction with objects in virtual reality when they are well aligned spatially and their physical form well matched, 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 in virtual reality. These assembled physical proxy objects are composed of magnetically attached blocks which are assembled by a small multi robot platform, 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 and assembled tangible interfaces in 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

INTRODUCTION

This paper explores a system allowing the creation of haptic proxy objects to support tangible interaction in virtual reality, using low-cost assembly and self-assembly of magnetic blocks at run-time.

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Recent advances in display technology and computational power have allowed virtual reality (VR) to once again seize attention both in academia and industry. While today‘s VR displays have developed to provide immersive experiences, further research is still required to support realistic haptic feedback for tangible interaction in virtual reality. Haptic feedback and tangible interaction are a key part of our experience in the physical world and allow us to dexterously manipulate objects and our environment.

Researchers have investigated and developed various haptic technologies to try to solve this problem. While many of them improve certain aspects such as grasping [1, 4] or kinesthetic feedback [21], 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 [11, 15] or virtual object manipulation [9, 30]. The disadvantage of these rigid props is that they either require users to have many objects on hand or appropriate objects that might not match well. Props can also be manufactured using digital fabrication and rapid prototyping technology such as 3D printers. Yet, current techniques can take up to several hours to build objects, and thus cannot provide users at run-time with haptic proxy objects for manipulation.

Another approach to enhance the tangible interaction in VR is through the concept or vision that Ivan Sutherland had for the Ultimate Display where "a room within which the computer can control the existence of matter" [32] or Hiroshi Ishii’s vision of Radical Atoms in which "a new matter capable of changing form dynamically" is used for interaction [14].

Research on self-reconfigurable robots, collaborative construction robots and shape displays has made promising steps towards Sutherland's and Ishii's vision. However, these systems still exhibit some limitations. Current self-assembly and collaborative construction robot systems operate in speed unsuitable for VR. As VR researchers in previous decade/century suffered from slow and low resolution screens, high refresh rate is key for compelling immersion and interactivity in VR experiences. Recent work on shape displays has helped expedite the process. inFORM [5] is able to form any arbitrary 2.5D shape almost instantaneously. However, current shape displays are not well suited for VR applications as these are grounded systems in which users can only feel and touch but cannot pick up or manipulate freely and are extremely 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 Zooids as the main platform/robot system, 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, success rate, and efficiency (time per robot). This serves as a guideline to decide which method to employ in different VR applications.

In summary, our contributions are:

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

BACKGROUND

Haptics for VR

To incorporate touch in VR, many researchers have developed active haptic devices to create virtual forces, both tactile and kinesthesia [8]. Some have focused on specific type of haptic sensation such as grasping [1, 4], kinesthesia [21], and tactile [33] while others attempt to provide more complete haptic sensations by combining different actuators such as adding skin stretch device to a PHANTOM [21].

In contrast to active haptics, passive haptics aims at using existing objects to provide haptic feedback [11]. Passive haptics has been used for medical volumetric data browsing [11], scientific visualization [15], 3D modeling [30], interacting with user interface elements [19], and at a larger scale, representing entire rooms or spaces [12]. Passive haptic props can be generic or accurate physical models, fabricated by precision CNC machines [18], however, the closer the alignment the better the manipulation performance [16] and sense of presence [12]. Previous research on tangible user interfaces have explored using haptic proxy objects as handles for virtual content, however the phicons often do not fully match the represented objects [13]. Other systems have allowed developers to have a large class of physical props that can be appropriated for use in VR [9]. While some researchers have leveraged other users to reposition and assemble large scale haptic proxies [3]. Very few have explored robotic assembly of hand held proxy objects.

Programmable Matter

Although providing virtual forces can be an effective way for VR 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" [32], then we can provide the exact haptic sensation in VR. Two approaches to achieving this vision of programmable matter [7] 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 [24]. 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 [5], change between states using pneumatic actuation [34], and leverage smart materials such as shape memory alloy to manipulate surfaces [26]. Other researchers have begun to explore constructive assembly with shape changing blocks, such as the Changibles system which requires external manual assembly [28] and using articulating and reconfigurable modular robots [27]. However, shape-changing interfaces have not been explored greatly in the domain of VR and few have explored self-assembly and assembly in this context.

Self-reconfigurable Robots

As mentioned by McNeely [22], "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 its shape 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. uses PolyBot, a self-reconfigurable robots to reach the goal of locomotion and manipulating different objects [35]. John et al. designed M-blocks, a system of cubic modular robots driven by momentum and can connect with each other by magnetic force [25]. Other researchers have explored using active systems for latching, such as electro-permanint magnets, coupled with external vibration for placement and alignment [6]. 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, enables robots to build more complicated structures given the same amount of resource such as number of robots albeit increasing construction time. Collaborative construction robots enables construction with passive elements allowing to build more with less. For instance, TERMES [23] can build complex structures with only three robots, using a distributed algorithm. Different actuations have also been used for collaborative construction: Lindsey et al. use quadrotors to build cubic structures [20], while Schoessler et al. utilize shape displays [29], and others use magnetically actuated microrobots [2]. Depending on the available resource, collaborative construction robots can be more suitable than self-reconfigurable robots.

CHALLENGES FOR ASSEMBLY SYSTEMS IN VR

While the robotics research community has explored assembly of modular objects, their application to VR and HCI introduces new non-trivial challenges.

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.

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 for VR. To this end, haptic proxy objects should be disassemblable using re-usable 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.

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 attempt to tackle these challenges using currently available technology at a relatively low cost, using simple robots and a simple connection strategy - magnetic blocks. We do not explore active disassembly or focus on optimization of block placement, though these are discussed in future work.

IMPLEMENTATION

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

We used Zooids [17] as a platform for our assembly system, which contains a group of swarm robots. The robots can be controlled by a central server through 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 [17]. We have modified them to have an external shell with integrated magnets.

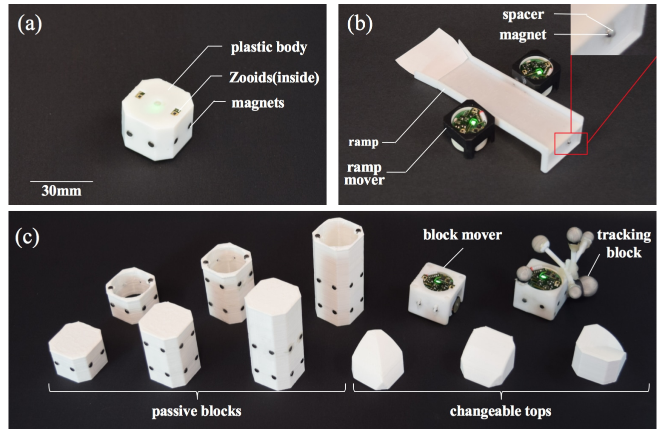

Figure 2: a) An active block consists of a shell containing a Zooid and magnets distributed around its surface to snap with other blocks. b) The ramp is actuated by two Zooids and allow active blocks to climb on top of each other. c) Passive blocks come in various shapes to allow to create more diverse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

Magnetic blocks

Blocks for active method

For the active method, we designed the magnetic building blocks as an external shell in which a Zooid can fit into. As shown in Fig 2(a), the shape of the blocks are designed to be a 28mm $\times$ 28mm $\times$ 22mm cube and on each of its four sides, there are two embedded magnets, which are oppositely polarized.

To extend self-assembly for 2-layer structures, we also designed a ramp controlled by 2 robots as shown in Fig 2(b). Rails on the sides of the ramp allow robots to climb up the ramp without falling.

Blocks for passive method

For the passive method, there are three types of blocks, as it is shown in Fig 2(c). One type of them is a passive block. The passive blocks are 28mm $\times$ 28mm $\times$ $x$mm cubes. x represents the height of block and has different values. The taller blocks may have two layers of magnets. On the top of some blocks there are two magnets making the shape of top changeable. The inside of the passive blocks is empty and the total weight for a single one ranges from 4 to 10 grams. This is important to minimize the force needed to move the blocks.

We show the second type of blocks in Fig 2(c), which are used to move the passive blocks. On one side of this block, there are two metal parts which are used to connect to the passive block. A plastic spacer outside the metal parts are used to limit the magnetic force so that it's strong enough for picking up the block and also suitable for disconnection when the block is assembled. More details about disconnection mechanism are discussed in the following section.

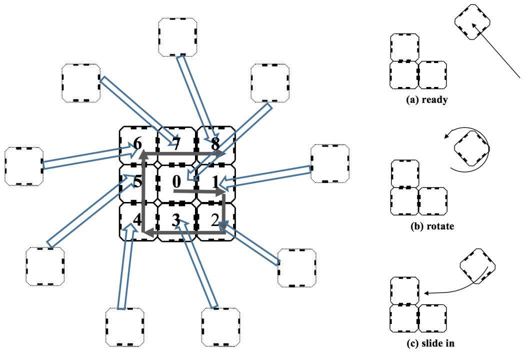

Figure 3: The active method starts the assembly by the center of the object and add blocks by growing outwards (left). Each block adjust its orientation before docking to maximize the chances of success (right).

Shown in Fig 2(c), the third type of block also has robot enclosed inside and is used for tracking the position of the structure, because with only passive blocks the Zooids system cannot know the position of the assembled structure. Mounted with retro reflective markers, this tracking block can also be used for spatial position and orientation tracking in VR using a motion capture system, such as Opti-track.

Besides the blocks, three types of changeable tops were designed: an outside corner, a fillet and an inside corner are designed to show more details of the surface. This allows for higher-fidelity shapes to be assembled.

Active Method

For the active method, with an actuated robot inside the basic building blocks, the blocks can move and report their position and orientation. There are magnetic components that surround the blocks so that they can connect with each other when they get close enough. The structure is assembled by commanding each block to a target position.

Assembly Sequence

For each assembly method, high level sequence planning is needed to avoid collision between blocks as well as to minimize assembly time. Moreover, when a block is assigned to a location which already has two blocks on either side, there is a large chance it will get stuck. Thus, our sequence planner should try to avoid this "narrow gap" situation. Considering all the reasons above, we choose an assembly sequence which starts from the center of the structure and rotates out spirally. One example for this sequence planning strategy with nine blocks can be shown in Fig 3, where the number on the block and the arrow show the assembly order. Using this planning strategy, we can guarantee that there will be only two situations when we assemble the block, a direct case and a corner case, and no narrow gap case will occur. Here the direct case means there is only one block out of four surrounding the target position before a new block is moved to the target. And the corner case means there are two blocks surrounding the target position.

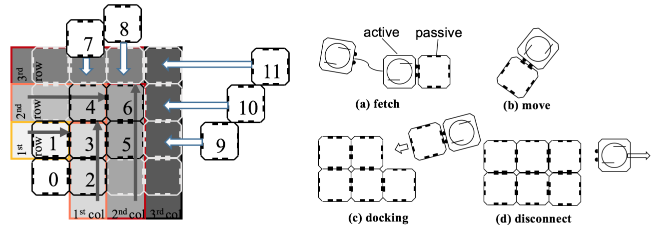

Figure 4: The passive method starts the assembly from the left bottom to the right up line by line(left). The actuated block mover will fetch the passive block and push it to the target position(right).

At the beginning of assembly, the active blocks will surround the structure and keep idle. The assignment will try to minimize the total moving distance of the active blocks. An example of an idle position assignment for nine blocks assembly can be shown in Fig 3, where the dotted-lined boxes show the idle position and the hollow arrows show where the blocks finally go.

Docking

The process for each block's assembly can be shown in Fig 3. The block is first sent to the ready position, which is several block sizes away from the target position. If the block needs to be assemble to a corner position, the ready position is set to be in diagonal to the target. Then the active block will adjust its orientation, then slide 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 Zoods system is roughly 1-2cm.

Self-assembly into 2-layer structures

For self-assembly of 2-layer structures, we used a row by row assembly sequence to minimize the distance that the ramp has to move. After self-assembly each row of the first layer, we determine whether a second layer is necessary. If so, then 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 as necessary for each robot on second layer. It was necessary to move the ramp around rather than having a ramp fixed on one location because robots had difficulty moving around on top of first layer robots due to its uneven surface. Currently, we only support two layer structures, but it is not impossible to use larger ramps to reach to higher levels.

Passive Method

Using active blocks the target structure can be assembled quickly with a relatively simple control strategy. However, the active blocks method still has several shortcomings. Since each building block needs one integrated robot to locomote, the robots needed to form a given structure will increase proportionally with the target configuration complexity. Thus, we also explored active assembly of passive blocks, to decrease the number of active components needed.

Assembly Sequence

Unlike the active method for which all the blocks have the ability to move themselves, the building blocks in the passive method need to be fetched and moved from a specific position to the target position. So we cannot use the technique of setting the ready position for the active blocks before they get assembled, which can decrease total assembly time. Another issue in using passive assembly is that after a robot has added a passive block to the structure, it may fail to disconnect. Then the robot will remain connected to the structure and wait for next passive block to be assembled, which will help the robot be disconnected through vibrations caused by the other assembled block. Considering the challenges above, the assembly sequence for passive method organized on a 2D grid is designed as follows:

1. If all blocks of which the target row index less than i and column index less than j have been assembled, go through the $i+1$ row and assemble all possible blocks from left to right. For those blocks, robots will move from up to down;

2. Go though the $j+1$ column and assemble all possible blocks from bottom to top. For those blocks, robots will move from right to left;

3. Repeat the steps above with row index $i+1$ and column index $j+1$.

An example of passive method sequence planning can be shown in Fig 4, where numbers and the arrow show the assembly order.

With this assembly sequence, we can guarantee that no narrow gap conditions will occur. Also even if one robot is not successfully disconnected, this method will try to minimize the influence of it because the robot will not occupy the space of the blocks in same row or column. Of course this algorithm will not work for all complex geometry structure and topology but works well enough for the structures mentioned in this paper.

Fetching and Loading

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

Fig 4(a) shows how robots fetch and load the passive blocks. The robot will first move close to the block and change the orientation so that the metal parts of the active block can face the target passive block's magnets. Then the robot will drive slowly to the target and magnetic force will help two blocks connect to each other. To make the connection stable during locomotion, robots will always push the passive block. The shape of the ferromagnetic metal connectors are spherical so that they allows some rotation between active block and passive block when they are connected. The height of these connection points are lowered in the robot so that the passive block is tilted to only have a single edge in contact with the ground surface so as not to over constrain the system and lower 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 so that the block will not get stuck.

Unloading

Since we need to reuse the robots and make space for the new incoming blocks, the robot should be able to disconnect from the assembled structure. There are two strategies used to make the robot not only move and rotate the blocks but also disconnect from the assembled structure. The first strategy is that we carefully designed the height of the ferromagnetic connectors on the active blocks, which are made to be slightly different from that on passive blocks (see Figure 5). When the robot installed in the active block is trying to move a single passive block, since the ferromagnetic metal connector is spherical and the passive block can rotate, the passive one will be attached to the active one at an angle. However, when the block is assembled to the structure, the total weight of the assembled structure will be heavy enough to pull the passive block down and make the disconnection happen. The second strategy is that when a new block is pushed to be assembled to the structure, vibration will be generated by the force of docking, which may spread throughout the whole structure. It may help any active robots which are still connected to the structure to disconnect.

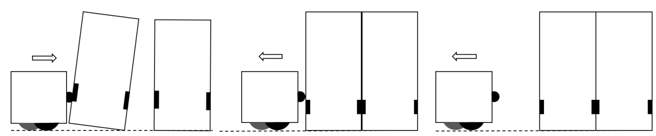

Figure 5: Docking magnets on passive blocks are slightly misaligned to facilitate transport and disconnection.

VR Setup

We use an Oculus Rift as the VR headset. Also 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 Zooids projector-based tracking only provides 2D position and orientation, so while it is used for assembly it cannot be used for 3D interaction. We use an OptiTrack system to get the position and Euler angle of the tracking block. Since we know the tracking block's relative position in the assembled structure, the system can then automatically calculate the transform of the object's center. All the scenes for different use cases are built using Unity.

TECHNICAL EVALUATION

In order to evaluate both methods and compare them, we use the same target shape to form, and the completion time and success rate of each method are measured.

Evaluation for active method

The target configuration for active method is a 3×2 rectangle. The total time and success rate for finishing the 1st to 6th

# of trials	Success rate
36	44%

Table 1: Success rate for each stacking

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 2: Mean completion time with standard deviation for each stacking.

# of failed trials	Ramp misalignment	Robot stuck
20	75%	25%

Table 3: Failure source breakdown for stacking

assembly were recorded. We repeat the experiment 21 times and the results are shown in Fig 6. According to Fig 6(a), the success rate remains 100% for the first two robots and decreases with the increase of the target blocks number. The final success rate is 85% for 6 blocks. The main reasons for failure is that a block gets stuck or a block is assembled to the wrong position.

From Fig 6(b), the assembly time shows a linear relationship with the number of blocks, which is reasonable since it's a linear sequencing method. The average time for assembling one block is about 3s.

For self-assembly of 2-layer structures, we evaluated the success rate and completion time breakdown of each time a robot block is placed on the top layer, and failure source breakdown is shown in table 2, 1 and 3. Of the 36 stacking trials, 16 of them were successful (44%).

For the successful trials, the completion time for three parts of stacking(prepare, climb, and remove ramp) were measured.

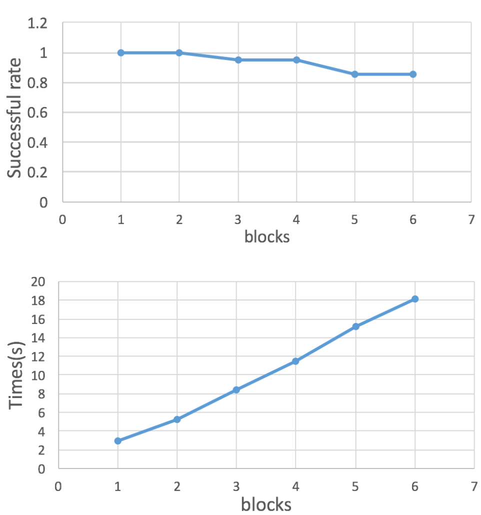

Figure 6: Success rate and completion times using the active method.

Climbing up the ramp had the largest mean completion time followed by preparing the ramp and removing the ramp. For climbing up the ramp, there is a large standard deviation in completion time because there were three cases in which the robot was stuck on the bottom of the ramp for a long time (>20 secs) but eventually was able to climb up the ramp.

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 to minimize the ramp misalignment and also by using better control for the robots.

Evaluation for passive method

For the passive method, a similar evaluation with a 3×2 rectangle target shape was done. We ran our evaluation with two and three active robots to see the effect of using different number of robots. As shown in Fig 7(a), 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:

1. All robots fail to disconnect from the assembled structure and no active block is free, causing the assembly process stop.

2. The passive block is pushed to the wrong position, mainly because of the error in position control and the robots' position tracking.

3. The block get stuck when it is pushed to a corner.

The evaluation results also show that when more robots are used, the assembly process can get a higher success rate. This is because with more robots, the probability that all the robots fail to disconnect will decrease. For example, with three robots, even if one robot fail to get disconnected from the block after assembling it, we still have two robots and when they continue

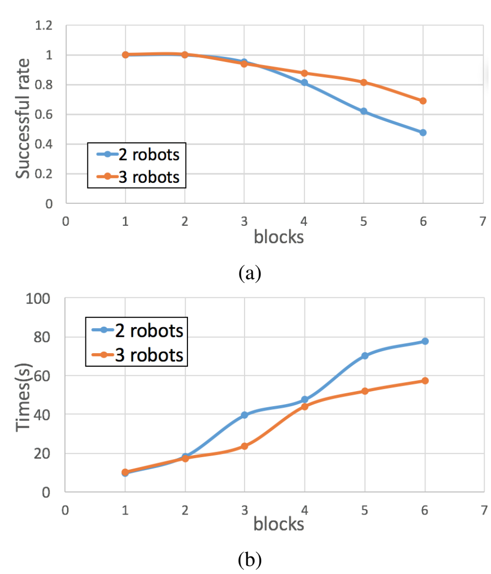

Figure 7: Success rate and completion times using the passive method.

to assemble blocks, the caused vibration will have a higher probability to help the connected robot disconnect.

Fig 7(b) shows the assembly time for the passive method. The evaluation show a non-linear relationship between time and number of blocks. This is because the assembly process is done turn by turn, namely robots fetch the passive blocks together(in order to avoid the collision), assemble one by one and then go together to fetch the blocks again. As a result, 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 turns. For this reason, we can see that when more robots are used, the assembly process can be faster. The evaluation shows that for 3 robots, compared with 2 robots in total, the average time to assemble one block will drop to 9.6s from 12.8s.

From the evaluation, it can be shown that the time for building a single block in passive method is 3 to 4 times to that of active method, showing the passive method is much slower than the active method. However if we look into 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 20.5s while assembling the blocks takes 2.7s. So if we have an algorithm that can avoid all the possible collision and pipeline the assembly process, i.e. whenever an block is assembled, the following block will be at the ready position for docking, then the total time for this ideal passive method would be $(20.5+2.7x)$s, where x is the blocks number. In this case the passive method can have a similar speed compared with the active method.

USE CASES

Shape Display

Using the self-assembly system, we can render different shapes with physical proxy objects. Fig 8 shows two examples of how we interact with virtual objects in VR by manipulating the proxy object. As the user moves the finger along the virtual object's surface, she can get an overall idea of the shape of the object as well as its weight despite the approximations of the proxy object due to the low resolution.

We can potentially render complex objects, as shown in Fig 1, using blocks of three different heights. This example is assembled by hand since a higher assembly successful rate is needed to get the shape with this scale using our self-assembly system.

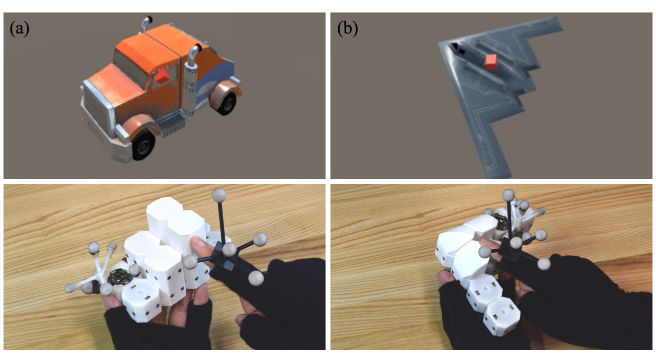

Figure 8: Assembled haptic proxy objects allow to manipulate and interact with various virtual objects.

Self-configurable Interface

The shape display can provide the user with haptic feedback when they hold and manipulate the virtual object. Under this situation, our system can be recognized as a haptic output device. The user can also adjust the position and the orientation of the assembled object according to the virtual scene, making our self-assembly system an input device for VR application. The application then automatically generate interface with different shapes according to the scenarios. Here we describe several applications, all of which do not require extra hardware.

3D Virtual Drawing

With the tracking block assembled with a taller passive block, we can provide user with a pen-like interactive tool. The user can then manipulate the assembled proxy in the physical world, the virtual pen is rendered in the virtual environment accordingly, by tracking the position of the constructed block, alongside with its trajectory.

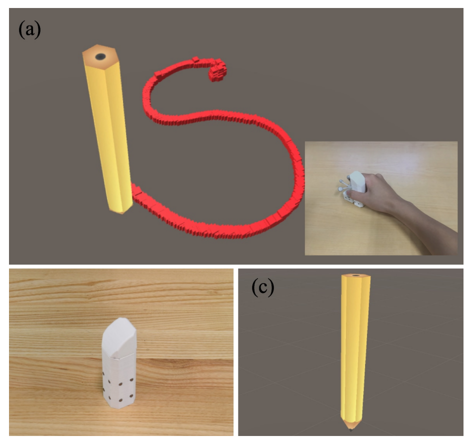

Figure 9: One can draw in the virtual world by manipulating using an assembled pen proxy.

Interface with Orientation Tracking

In this scenario, we assemble a shooting gun and then use the orientation of the virtual object as an input. As shown in Figure 10, manipulating the proxy gun allows to aim and shoot accurately. The assembled shape provides not only the user a gun handle to grab, making the experience more realistic, but also extend the position of tracking block to make a higher precision of orientation tracking.

Interface with Virtual Switch

If we treat the assembled structure and the virtual object as one rigid body, it will only have six degrees of freedom. However since the blocks are connected by magnetic force and can be disconnected and reconnected when manipulated by user, if we track more than one position of the assembled structure, it will allow more degrees of input.

Fig 11 illustrates this approach. The building blocks for this interaction method in Fig 11(c) include two blocks and a trackable top. According to the design of top, if we push the top to break one of the magnetic connections, the top will rotate along the rest magnet. Our tracking system can detect the distance changes between the top and the main body of the object, using which we can either open (Fig 11(a1)) or (Fig 11(a2)) close the switch for beam.

Interface with Position Mapping

For all the applications described above, the position of virtual object is mapped to the proxy object. However in some application, the virtual object may have some constrains in movement. Even though we can not provide those constrain in real world, we can map the virtual object to obey the constrains in virtual world. As shown in Fig 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 plate, while the real assembled object can be moved freely. We just read the position of the assembled structure on this direction as an input and use this value to render the virtual object.

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 mainly to two factors - 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 more positional 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 robot to re-position in case they docked in the wrong position.

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, a better planning and scheduling algorithm, could improve assembly time. Finally, faster robots could obviously improve the speed of assembly, though it is likely to reduce positional accuracy, and thus may not improve overall completion time.

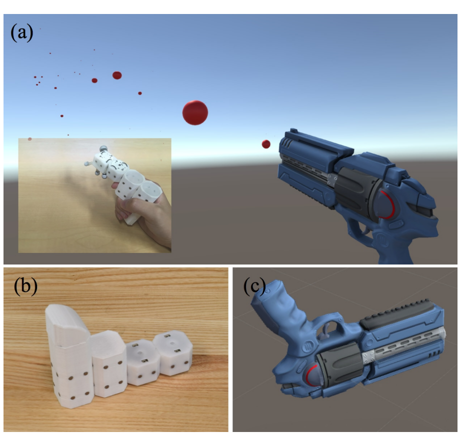

Figure 10: Tracking the orientation of this assembled proxy gun allows to aim and shoot accurately.

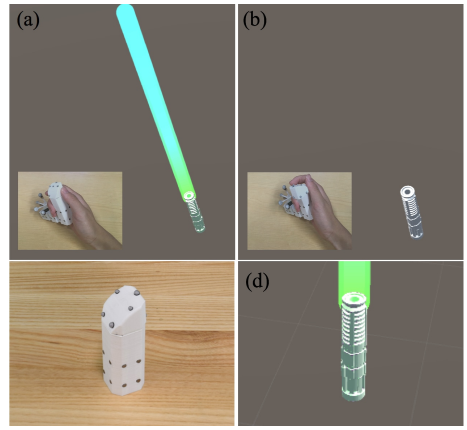

Figure 11: The assembled proxy light-saber includes a secondary marker. Flicking this top marker allows to open and close the light-saber.

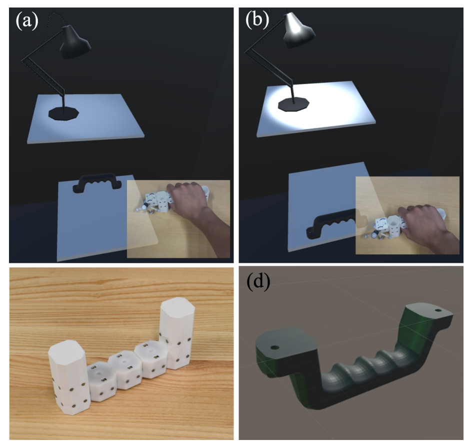

Figure 12: Moving the assembled proxy switch allows to control the intensity of the light in the virtual world.

Spatial Resolution - It has been shown that resolutions of 2-3mm are needed to accurately represent an object for haptic perception of shape [31]. 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 hard to create much smaller multi robot systems often due to the power train and actuation technology. Moving to wireless power distribution and other actuation technologies, piezo or magnetic, could reduce the size. In future work we could also imagine combining 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 fit represent a given high resolution model.

Disassembly - Because our system uses permanent magnets for assembly it requires users to manually disassemble the proxy objects to be reused. Higher torque motors or an unlatching mechanism could enable the active blocks to disassemble. The passive blocks could use electro-permanent magnets [6] 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 shearing 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 blocks, higher torque robots would be needed, or more robots working together.

External Digital Assembly - Self-assembly and robotic assembly using small mobile robots has great promise in the future, but as described in this section many limitations. 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 [10]. We imagine these types of printers could quickly generate low resolution forms 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 assembly of 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 applications in virtual reality. Our demonstrations, while simple, already highlight some meaningful uses 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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