TanGo: Exploring Expressive Tangible Interactions on Head-Mounted Displays

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ABSTRACT

We present TanGo, an always-available input modality on VR headset, which can be complementary to current VR accessories. TanGO is an active mechanical structure symmetrically equipped on Head-Mounted Display, enabling 3-dimensional bimanual sliding input with each degree of freedom furnished a brake system driven by micro servo generating totally 6 passive resistive force profiles. TanGo is an all-in-one structure that possess rich input and output while keeping compactness with the trade-offs between size, weight and usability. Users can actively gesture like pushing, shearing, or squeezing with specific output provided while allowing hands to rest in stationary experiences. TanGo also renders users flexibility to switch seamlessly between virtual and real usage in Augmented Reality without additional efforts and instruments. We demonstrate three applications to show the interaction space of TanGo and then discuss its limitation and show future possibilities based on preliminary user feedback.

CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

KEYWORDS

Mobile Devices, Input Techniques, Touch, Haptic, Pointing, Gesture, Virtual/Augmented Reality

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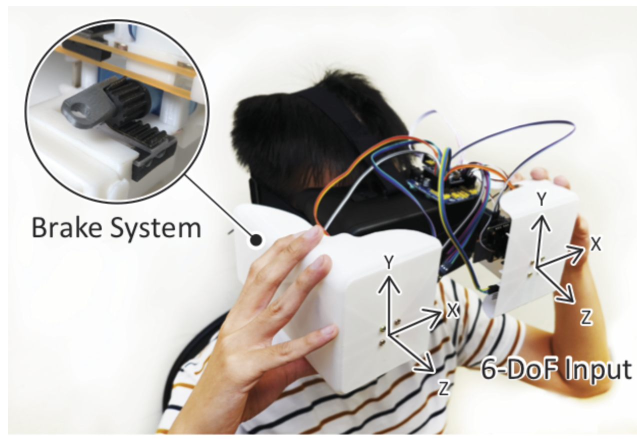

Figure 1: TanGo provides 3-dimensional input on both right and left side with resistive force output coupling through the brake system.

1 INTRODUCTION

VR/AR has recently brought us unprecedented experiences and advanced progressively from physically onerous instrumentations (e.g. HTC Vive [2]) to now standalone Head-Mounted Display(HMD) (e.g. Oculus Go [5]) with hand-tracking technologies enabled (e.g. Oculus Quest [4]). Moreover, the smartphone-based VR, called nomadic VR by Gugenheimer et al [12–14], is under development and allow users to access Immersive Virtual Environments (IVEs) by its omnipresence. However, little of above-mentioned examples take advantage of spaces of HMD as input.

Increasing HMD Input Modalities. Prior research and commercial products have been exploring augmentation of input modality on HMD, showing this area of work is promising and valueable. For example, low-cost VR headsets, like Google Cardboard [1], provide magnetic toggle [29] or conductive tap on the side of HMD enabling binary input, and researcher then augmented this using different design [22] and the inner sensor of smartphone [35]. Another prior attempt at designing input on HMD is to explore the Back-of-device interaction; for instance, FaceTouch [13] attach the touch panel on the backside of VR headset to allow users to support advanced point-and-selection tasks by the sense of proprioception and following with touch display to facilitate the communication with the outside users [8, 14]. FaceWidgets [33] places multiple widgets on the HMD backside to allow tangible interaction individually and provide always-available input.

Beside the unexplored space of HMD input, output feedback is also limited with only vibration provided for commercial products. Though prior research explored different types of haptic output, they mostly depends on the context of applications [9, 15, 25, 26] but, unfortunately, not coupling with user input. Output along with input has demonstrated the promise to enable novel experiences and interesting applications on different instruments [16, 17, 31]; for example, users can acquire information through levels of haptic profiles [16, 17, 31]. This type of haptic output features its rich resistive force profiles while only requiring lightweight structure, with one motor or servo in each DoF. This mechanism is ideal to HMD due to the necessity to carefully trade off size and weight to avoid fatigue [13].

To explore expressive input and appropriate output feedback for bimanual manipulation on HMD, in this paper, we proposed TanGo, a proof-of-concept prototype equipped on off-the-shelf mobile HMD. TanGo comprises three Degree of Freedoms (DoFs) (x, y and z axis) in both right and left sides of HMD. Each axis is realized by a slide potentiometer, two rubber band, a micro servo, a brake pad and 3D-printing support. Inspired by joystick, the middle point of slider serves as the origin that users could slide the 3D-printing shell in two directions and rebound to the origin after releasing. When input is being applied, servo would adjust the tightness between brake pad and the sliding structure, generating totally 5 resistive force profiles, including lock, click, ramp up, ramp down and strong resistance.

We demonstrate TanGo's applicability in three simulations. In the first-person (FPS) exploration game, TanGo can manifest directionality that users can move backward/forward to open/close the drawer, and slide left/right to open/close the sliding door with the strong resistance provided to simulate real friction. Object can be manipulated by gesturing "open" in x-axis with lock following to shape the object held in hand, and can afterwards drop down by stretching down y-axis. In the tank game, the fire can be triggered by stretching down the y-axis coupled with resistive force ramp down to simulate gun trigger. Users can also navigate the tank intuitively by moving TanGo forward/backward bimanually to drive forward/backward, and turn left/right by crossing slider in z-axis. In AR scenario, users can interact with virtual objects by manipulating TanGo and instantly switch to the real world in barehand. TanGo can seamlessly bridge the real and virtual world while minimizing the physical efforts.

In this paper, our main contributions are:

(1) TanGo, an all-in-one proof-of-concept prototype enabling always-available input with high expressivity that can support bimanual gestural interaction, coupling with 6 passive kinesthetic force outputs, including lock, click, ramp up, ramp down and natural and strong resistance.
(2) Three demonstrations showing the feasibility of TanGo to general complex VR/AR scenarios with the advantage of supporting seamless interaction between real and virtual.
(3) A preliminary user feedback revealing the first impression of TanGo and the potential design space for future tangible design on HMD.

In the rest of the paper, we first elucidate the inspiration from related research, then the implementation of TanGo in details. Lastly, we demonstrate the potential usage scenarios of TanGo and the preliminary user feedback that enlighten future works.

2 RELATED WORK

TanGo is inspired by previous works related to input techniques in VR and kinesthetic feedback on different appliances.

2.1 Input Techniques in Virtual Reality

2.1.1 Hand-held Controllers. Hand-held controllers serve as most widely-used input today. However, commercial devices, like HTC Vive [2] or Oculus [5] controllers, require onerous environment setup and provide limited interaction space contrary to the nature of nomadic VR [12]. Previous research also exploited different appliances such as smartphone [24], smartwatch [21], tablet [7, 30], pen [6, 7] as controller proxy, enabling different interaction space in virtual reality. Other hand tracking technologies, like Leap Motion [3] or Oculus Quest [4], can support free-hand interaction and no spatial constraint, however, demanding hands within the camera view which cause missing tracking often time.

TanGo is mediate between HMD and hand input as a hand-controllable device mounted on the HMD. Our aim is not to replace existing input devices but to explore a new input modality allowing users to transit between bare-hand and tangible interactions fluidly by its always-available feature (as following AR application suggest), and importantly, coupled with rich output feedback as following illustrated.

2.2 Kinesthetic Feedback along with User Input

2.2.1 User data as reference for output providing. Kinesthetic force feedback is mainly applied under this scope since it refers to the feelings sensed from the nerves in the joints and muscles, which make users aware of continuous proprioceptive changes when carrying out actions. Resistance along with user input is previously applied on different appliances such as chair [31], ring [17] and mobile module [16]. Such feedback can effectively offer users levels of information using highly recognizable force profiles even under eyes-free condition. Glissade [19], instead of generating resistance as above, dynamically change the center of mass and moment of inertia based on user's action (e.g. tilting and rotation), in which different patterns can act as haptic cues to support user's tasks. For the VR controller, Dexmo [11] is analogous to our work by providing passive force feedback based on angle difference of Metacarpophalangeal joint of fingers. RollingStone [23], as one of few examples of tactile feedback under this scope, considers the speed of user's hand movement as reference to adjust the speed of the actuated ball to create different textural feelings. The main benefit is to yield rich haptic feedback while keeping low-cost and lightweight with only one motor or servo needed for each degree of freedom.

2.2.2 Kinesthetic Force Feedback on Controllers. Kinesthetic force feedback has also been widely explored on hand-held controller to generate different sensation. Prior works like Shifty [38]and Transcalibur [27] render different virtual weights, sizes and shapes by distributing device's balance. Thor's Hammer [18] and Aeroplane [20] offer different weight and force illusion by changing the propeller propulsion within given directions. Drag:on [37], on the other hand, create air resistance by altering the surface area of the device. CapstanCrunch [28] use the brake mechanism to support non-linear force mapping regarding to the finger-thumb distance. Such weight, shape and size sensation can also be generated by the lightweight wearable devices; Grabity [10], for instance, controls the unidirectional brake to generate kinesthetic pad opposition grip forces to simulate rigid grasping and the weight when lifting.

Inspired these works, we exploit passive kinesthetic force feedback to enforce different simulations and haptic status for enriching VR applications.

3 DESIGN AND IMPLEMENTATION

Prior works on designing mechanical structure on HMD [33, 34] suggested weight can be decisive to user experience and need to be tackled with. In this work, we carefully considered weight of TanGo.

We propose our proof-of-concept prototype *TanGo* through iterative refinement (Figure. 2). Basic features like input and spring return mechanism are implemented in version 1. The brake system was added in version 2. The weight of the system decreases even when new features are added. In version 3, we further cut off the overall size and weight. We next discuss the implementation and the trade-offs in this section.

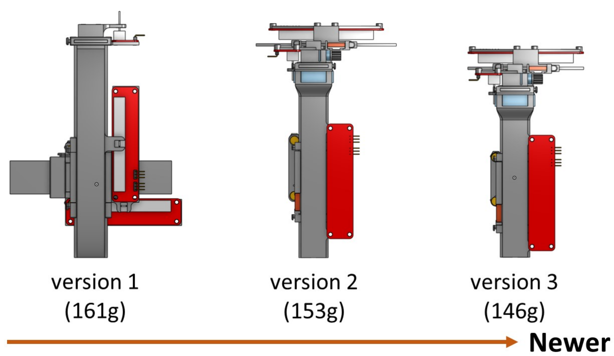

Figure 2: Prototype iterations and their weight (single side). Three CAD models are shown as examples. For better illustration, the shell and wires are not shown.

3.1 Overall System Configuration and Components

We choose off-the-shelf mobile HMD as the base of TanGo because, to our knowledge, it has the minimal size and weight among current commercial products (width 168mm, height 90mm, depth 108mm, weight 264.4g). We don't choose the cardboard HMD due to its vulnerability when being manipulated.

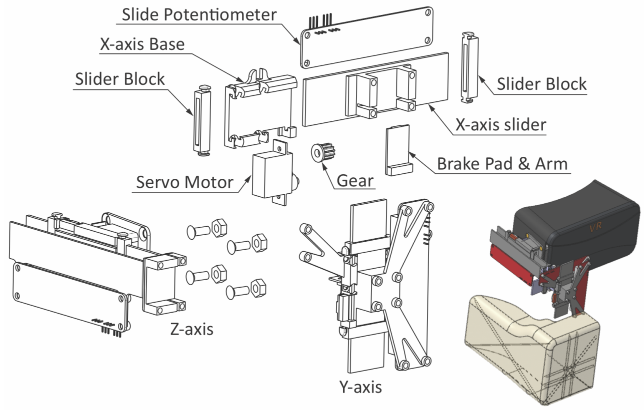

Figure 3: A prototype assembly explosion diagram of TanGo.

TanGo (totally weight 736.7g) comprises three axes and one shell on each right and left side (Figure. 3). Each axis has a sliding structure for input and a brake system to generate passive resistive force output, which will be illustrated in detail below. The whole mechatronic system is driven by a micro-controller (Arduino Nano and Nano Extension Board Module) and a power bank (HTC BB G1000, 10050mAh, 5 6V–3A,weight 228g). The data transition between Arduino and smartphone is through the bluetooth module (HC-06).

Some parts of the structure are hollowed out to reduce weight. We hollowed out the plane on which we mount the slide potentiometers (Figure. 4 a). Structural strength should also be considered when hollowing out the structure. For example, the z-axis is designed to be an I-beam to withstand the maximum amount of bending load while using the least amount of material (Figure. 4 b).

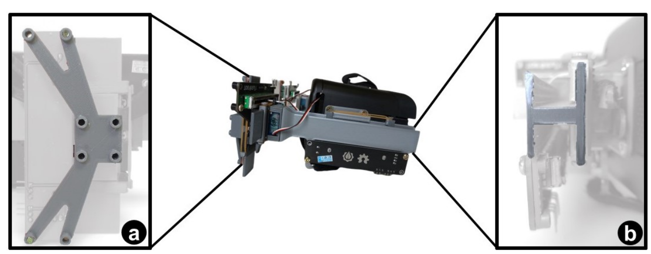

Figure 4: The skeleton structure after being hollowed out. (a)The frame to mount the slide potentiometer. (b)I-beam stick.

3.2 Sliding Mechanism

To perform intricate output profiles, the sensor of input should have adequate precision and sampling rate. We adopt slide potentiometer (YwRobot sliding potentiometer) as the sensing approach of TanGo because it meets these requirements, and its linear sliding motion fits the mechanism of TanGo.

To minimize the overall size, all sliding mechanisms should be parallel to the surface of the HMD. Top and bottom side of HMD is not a reasonable location, given that the structures will collide

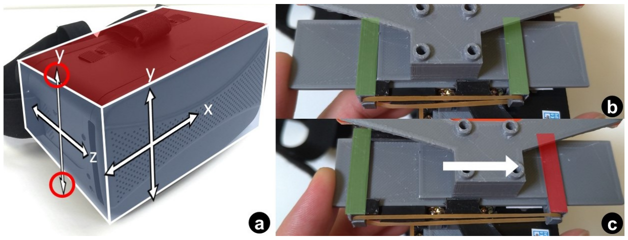

Figure 5: (a) The placement of coordinates. The y-axis on the side of HMD would protrude from the top and bottom if being manipulated. (b) The rubber band is initially pre-stretched. (c) Rubber band is further stretched when the user push right, generating restoring force for returning.

with face when being manipulated (red area in Figure 5a). TanGo is thus equipped on the left and right sides of HMD to have more work area.

A spring return mechanism on input devices can improve user experience, as it always pulls back to the origin after releasing, like button and joystick. Each axis of TanGo has this spring return mechanism consisting of 2 slider blocks and 2 rubber bands (Figure. 5 b). The rubber bands are pre-stretched at neutral position so that the restoring force, according to Hooke's law, is strong enough (1.3N) to return the slider even at minimal displacement. (2.21N at maximal displacement)

Because the working range of slide potentiometer is about 60mm, the maximal displacement in each axis is ±30mm. However, considering *size*, we do not use it all. Instead, we adopt ±20mm based on two reasons: 1. *Size.* As Figure 6 suggests, greater working range requires larger size of the shell. Though ±30mm can express input and output more explicitly, it will be too bulky to be held by users. 2. *Output.* The first mission of TanGo is to realize input and output smoothly, and secondly, keep compactness as possible. Hence, although ±10mm has the most appropriate size for holding, the output profiles cannot work completely in such small range. This is another reason that we take ±20mm as final decision.

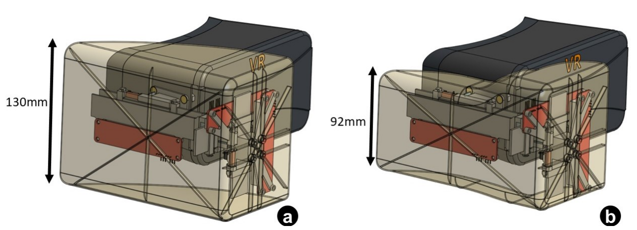

Figure 6: (a)Before and (b) after reducing the unnecessary space of shell.

3.3 Shell

Considering the usability, we designed a shell, acting as a handle for all input entries. Two shells cover left and right side of HMD with each can be maneuvered in x, y and z direction in ±20mm as mentioned. We firstly decide z-axis on the side and x-axis on the front of HMD. The y-axis on the side will protrude from the top and bottom (Figure. 5 a), making the shell impossible to cover all inside structures in a normal size for being gripped. We therefore place the y-axis in the front. We should also leave enough space between the shell and inside structures to enable the movement in both directions. To be more specific, since the displacement range of the y-axis is ±20mm, the shell should be 40mm taller than the HMD (height:90mm), which is totally 130mm (Figure. 6 a). However, because y-axis is placed on the front, we can reduce the side of shell to 92mm (Figure. 6 b).

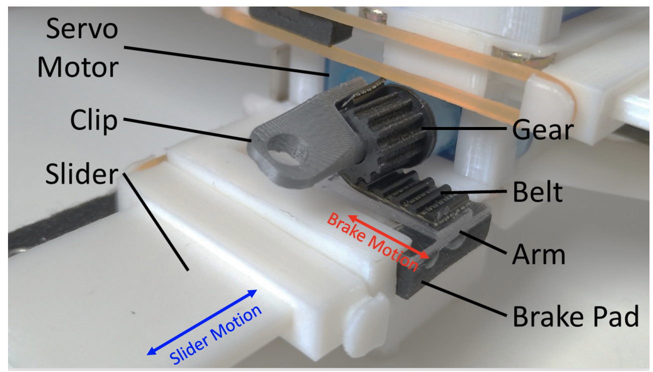

Figure 7: Brake system modulating the resistive force of the sliding mechanism.

3.4 Brake System

We use a mechanism similar to Aarnio [31] and Frictio [17] that provides resistive force output by the brake system. This system comprises a servo motor (3.7g micro servo, IM120602005, Torque : 0.7kg/cm (4.8V) 0.8kg/cm (6.0V)), a 3D printed gear, a 3D printed arm, a rubber brake pad, and a piece of belt. The gear is wrapped by the belt with a clip clenched to prevent slip, as shown in (Figure. 7). The brake pad is made of rubber because of its durability (the ability to withstand abrasion) and high coefficient of friction, which is important that if the brake pad is worn out and cause thickness change, we would have to re-map the resistive force profile.

By using this system, desired resistive force can be realized by adjusting the tightness of brake pad and slider. Due to the inaccuracy in the crafting of brake pad and 3D printing, each brake system has to be adjusted individually. We artificially mapped the angle of the servo motor to 5 resistance levels to ensure each axis can perform profiles correctly as expected. Totally, 6 distinctive force profiles can be performed by altering the angle of servo. We will discuss the details of force profiles in the next section.

3.5 Strap

To ensure *stability*, a set of strap is added to fasten TanGo to the user's head, as shown in (Figure. 8). Since the HMD comes with straps on the side and the top, we just need to reinforce the lower part. The strap is y-shaped so that it does not slip away from the user's chin.

Figure 8: User wears a HMD using the strap. TanGo is removed for better illustration.

4 RESISTIVE FORCE PROFILES

To demonstrate the kinesthetic haptic output of TanGo, we implemented 6 passive resistive force profiles tightly coupled with input in each DoF (Figure. 9). (inspired by SqueezeBlock[16], Aarnio[31] and Frictio[17]). However, due to the spring return mechanism, the resistive force feedback of TanGo contains returing force based on Hooke's Law by default, which changes along with the displacement in addition to the applied friction, as the following equation:

$$Resistive force = Friction force + Returning force \quad (1)$$

$$Returning force = k * \Delta X \quad (2)$$

The equation (2) is Hooke's Law, in which k is a constant factor characteristic of the spring and the ΔX is the displacement. In TanGO, the returning force (spring force) is 1.3N at minimal displacement and 2.2N at the maximal displacement. Hence, the curve of resistive force will linearly increase along with the displacement as Figure. 9 indicate.

Natural Resistance. In this profile, no additional force is applied by the brake system. The overall resistive force that users feel is from slide potentiometer, mechanical structure and the spring force of rubber band, ranging from 2.3N to 3.2N by displacement. In our applications, *Natural Resistance* is applied when no output is needed.

Strong Resistance. This profile is larger than *Natural Resistance* (from 4.8N to 5.7N by displacement) but we make sure users can still

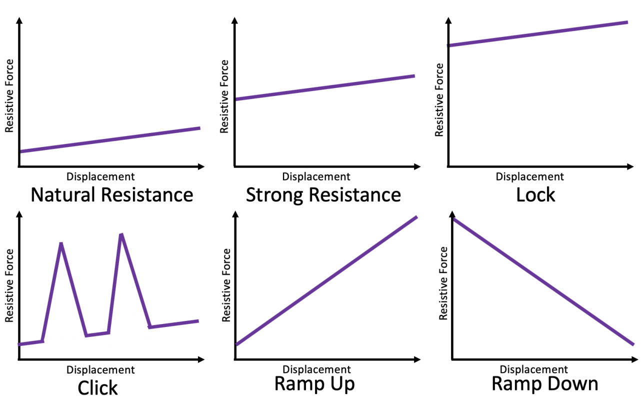

Figure 9: Resistive Force Profiles

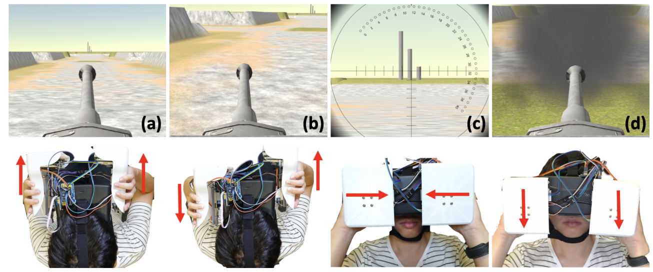

Figure 10: (a) User can drive forward by moving TanGo forward (b) and turn left by crossing in z-axis. (c) Aiming mode is triggered by squeeze gesture. (d) User can stretch down TanGo to fire.

manipulate TanGo with reasonable strength. *Strong Resistance* can simulate the friction of pulley block of sliding door or the weight of objects.

Lock. Compared to above two resistances, *Lock* has the highest resistance to stop users from moving the DoF of TanGo. By pressing the brake pad to the sliding structure tightly, TanGo can resist about 10.2N at minimal while 11.1N at maximal displacement, which effectively restrict the movement in usual cases. *Lock* can be conducted anytime to inform users of size or length of the object. For instance, when being opened x-axis to the end, TanGo can lock x-axis to indicate the largest box is held in hand; in contrast, small box would be locked on the way of movement depends on its size.

Click. The resistance level of *Click* alternates between *Natural Resistance* and *Lock* and can repeat during sliding. The frequency of *Click* can be adjusted to deliver different information. To exemplify, when scaling up the virtual objects, high frequency of *Click* is provided as the hint for users operating more accurately. *Click* can also simulate the operation between knob and key during unlock the door.

Ramp-Up. The resistive force starts from *Natural Resistance*, and increases linearly along with user input to *Strong Resistance* till the end. We adopt this mechanism to ensure user can still move TanGo but not being locked. Users gradually feel the slider should be pushed harder. *Ramp-Up* can be used to simulate the sensation of grabbing an elastic ball or tightening a bottle cap.

Ramp-Down. The working principle of *Ramp-Down* is similar to that of *Ramp-Up* but starting from *Strong Resistance* to *Natural Resistance*. Users feel easier to push *Ramp-Down* when sliding. This profile can create the sensation of gun trigger or unscrewing a bottle cap.

5 EXAMPLE SCENARIOS

To verify the capability of TanGo, we implemented two VR applications and one conceptual AR scenario, which exemplify various classical interactions, preliminarily demonstrated the promise of TanGo.

5.1 Tank Combat Game

This game delivers basic interaction techniques in general scenarios, like vehicle navigation, fire trigger and reload mechanism. Each

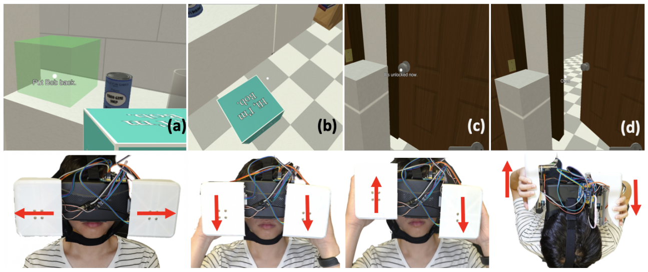

Figure 11: (a)When opening to the end, TanGo will lock x-axis to indicate box is held in hand. (b) User then can drop down by stretching down TanGo. (c) With the key held in hand (bottom right), user can make cross gesture in y-axis to unlock the door and (d) open it based on the direction.

action is provided appropriate haptic feedback to improve user experience.

5.1.1 Navigation. Navigating vehicles is a basic interaction for many games. In this tank game, users can move forward/backward bimanually to drive forward/backward (Figure. 10a). To turn left or right, users can cross their hands in different directions of z-axis as controlling the steering wheel in real world (Figure. 10b). This mechanism is designed to map parallelly to user's perspective for the sake of intuitive gesture control. *Natural resistance* is provided in this context because disturbance should be minimal to not influence user's control in such basic action.

5.1.2 Aiming. Aiming or sniper mode is common to FPS shooting games. To trigger aiming mode, users could make a squeeze gesture (Figure. 10c), like grabbing the telescope bimanually. During the movement of gesturing, *ramp-up* is provided to simulate that telescope is gradually being held in hand. This kind of output feedback can also inform users whether the mode is successfully triggered.

5.1.3 Fire and Reload. Fire and reload are both fundamental operations in FPS shooting games. From previous experiences, fire is mostly triggered by the button of controller while reload usually requires specific actions (e.g. pick up the bullets). In this scenario, TanGo demonstrate triggering fire by stretching down bimanully in y-axis (Figure. 10d) and reload by stretching up. As to output, *ramp-down* is provided to mimic the force feedback of gun trigger, or just like the button trigger in the regular practice. For the reload, we adopt *ramp-up* to simulate gun loaded.

5.2 First Person Exploration

FPS exploration game is another popular type of game. In this application, we demonstrate TanGo's adaptability to varied object manipulation with specific resistive force feedback coupled. The operation of this game is similar to current mobile VR that a crosshair/point cursor is centered in the FOV, so that the user can aim at the target by rotating their head.

5.2.1 Pick up and Drop down Objects. Picking up objects is essential to many games to launch further interaction. To simulate this action, users can gesture "open" in x-axis to the end, and TanGo will instantly *lock* the x-axis to inform user that something is currently held in hand (Figure. 11a). This technique is to simulate that people would open their hands first before grabbing the target. To drop down the things in hand, user can stretch down in y-axis (Figure. 11b), like putting down the object. TanGo will then release the x-axis immediately to indicate object is out of hand.

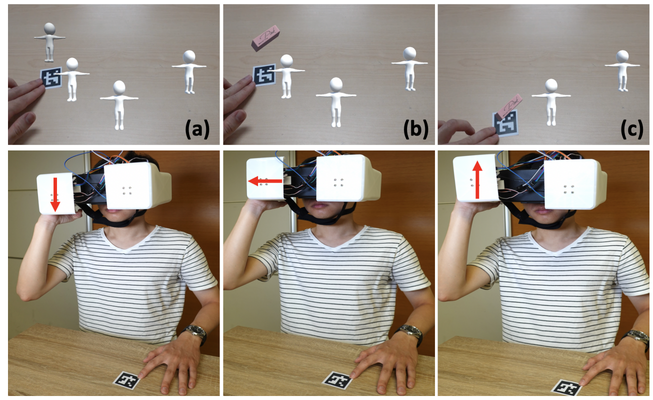

Figure 12: TanGo allows users to access virtual and real objects simultaneously. For example, they move physical paper code with left hand and use right hand to (a) move down TanGo to create, (b) move left to switch virtual target (eraser) and (c) move up to erase.

5.2.2 Open the drawer and sliding/swinging door. In this scene, TanGo can manifest directionality and spatial mapping. To open/close the drawer, user can move forward/backward to gesture like "pull" or "push" in our daily usage. Besides drawer, door is also applicable in this mechanism. There are two types of door, sliding door and swinging door. User can simply move TanGo left or right to open the sliding door. However, the swinging door additionally requires another dimension (z-axis) due to its structure. Hence, user should move forward with left hand and move backward in right hand to open the swinging door. When interacting with the three appliances, strong resistance would couple with the input to simulate the friction between slide rail and sliding door and the force generated by the door shaft of swinging door. (Figure. 11d).

5.2.3 Unlock the door knob. When the door is locked, user should first look for the key and pick it up by the foregoing pick-up gesture. With the key in hand, user can make rotational gesture in y-axis to unlock the door (Figure. 11c). When moving, *click* is provided to simulate the operation between key and lock. User can then drop down the key to free their hands to further open the door as above.

5.3 Building Village in Augmented Reality

Seamless interaction between virtual and real world. The high expressivity of input renders users multiple interactions with virtual objects and the seamless transition to real world without additional efforts and instruments (e.g. dropping down the controller to free occupied hand.), while the output feedback serves as haptic cues for improving addressing high-level tasks. TanGo mainly support two types of interaction: (1) *bimanual interaction.* Similar as above, users

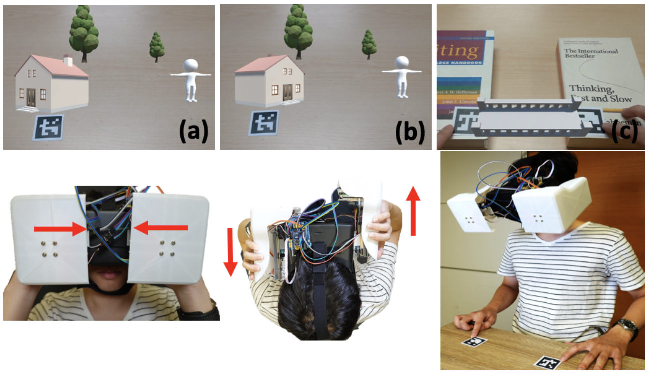

Figure 13: (a) users can scale down the tree by squeeze gesture, (b) rotate the house by crossing in z-axis and (c)seamlessly transit to real world bimanually.

make bimanual gestures on TanGo to manipulate virtual objects and can transit to physical world with both hands in anytime. (2) *unimanual interaction.* users can unimanually operate one side of TanGo with the other hand manipulating real-world things. We build a basic construction game that users can use the physical paper codes to construct their own village by gesturing on TanGo.

5.3.1 Moving, Creating, Erasing and Switching target Objects. The user (if right-handed) can firstly move the physical paper code with left hand and input gesture command with right hand on TanGo, where moving down to create current visible object (Figure. 12a), moving left or right to change different target object (Figure. 12b) and moving up to erase (Figure. 12c). Unimanual interaction allows two hands to cooperate with each other separately in virtual and real world.

5.3.2 Building the bridge. To build the bridge, users can first manipulate two paper codes bimanually to decide the length and the location of the bridge, then switch to the left or right side of TanGo to move up to create. This ensures users can seamless transit between virtual and real world in both hands. moving up to erase (Figure. 13c).

5.3.3 Scaling up and down the target. To scale up and down the target, users can gesture "open" and "squeeze" (Figure. 13a) gradually in x-axis with the *click* profile provided. The gesture is to simulate that people use the thumb and index to zoom in/out on their smartphone. *Click* is provided to accurately inform users the scale they currently operate.

5.3.4 Rotating the object mainly in two directions. Another basic interaction is rotate. After aiming at the target, users can make a cross in z-axis (Figure. 13b), so that the object will be rotate with the yaw as axis, while crossing in y-axis can render object rotation with the roll as axis. The clockwise or counter-clockwise depends on the direction of cross.

6 PRELIMINARY USER FEEDBACK

We demonstrated TanGo to 5 users (age from 23 to 30), two of them have prior experiences in developing VR/AR applications, one designer has experiences in HMD hardware design and the other two are gamers. During the experiment, participants first manipulated TanGo for two VR applications. And then, to efficiently elicit feedback about the proposed conceptual AR scenario, we adopted the feedback method [36], in which all participants were shown the video in first-person and third-person view, like Figure 13.

All users raised the comfort issues that TanGo cannot stay firmly when force applied even with straps. Some people also have fatigue problems because they kept holding TanGo while others didn't. However, no one concerned about the weight and balance since we designed TanGo in a light way and users hands can afford partial weight. Further, the designer suggested the handle should be designed as general as possible since the current size (92mm) is too large to be comfortably held in hand for some people. She also suggest having grooves on the shell would be helpful to make hands fit in and improve interaction. One gamer proposed that physical widgets can be added on the handle, like button or knob, to make TanGo a multi-functional device with more tangible interaction, like a combination with FaceWidgets [33].

For the output, all users commented that the *ramp down/up* are not noticeable enough and change discretely but not continuously as we expected. Otherwise, *Lock*, *Strong and Natural Resistance* are perceivable. Two users were frustrated on *Strong Resistance* as they cannot move smoothly as normal cases. We hope to find an adequate resistance value without disturbing user experience in the future. To the more appropriate output feedback, two people suggested that TanGo can additionally add simple active haptic feedback such as elastic impact [9] and normal force feedback [32] because TanGo allows them to rest hands during the application, where active haptic feedback can be a good addition during this period. We argue that this can be realized by modifying current elastic mechanism and adding another actuator on the target DoF.

All users were surprised about TanGo's novel input modality and highlighted TanGo should not be limited to virtual applications. A gamer mentioned that TanGo, based on his experience, can be an ideal controller of drone due to its 3D acting space, which is more intuitive and spatially reasonable than the 2D controller; in addition, if wireless technologies were allowed in the future, users can also see the view of drone through HMD and zoom in/out by gesturing, as a new page of drone experience. Some users commented that TanGo can be included to the board game due to its seamless transition between virtual and real property. Two users noted that TanGo can support multiple-players interaction such as tug of war, in which TanGo can render the pulling force, and collaborative games, where non-HMD user can move physical property, like paper code or recognized objects, while HMD user can manipulate the virtual things in the view.

To sum up, as the early stage of the design, TanGo raise issues regarding to the fatigue, usability and comfort, all of which lead the experiment to a short period (all within 30 minutes). In the following section, we summarize current constraints of TanGo and discuss possible solutions and future works.

7 DISCUSSION AND FUTURE WORK

We categorize the limitations from user feedback and our design process, and discuss gained knowledge and future works.

7.1 Limitation

Sensors. Sensors with high-resolution analog data and smaller size can be an ideal replacement of slide potentiometer for two reasons. First, TanGo can reduce the 3D-printing structure and thus decrease the overall weight and the size of the shell can be more suitable for being grasped. Second, with higher resolution, TanGo can support more subtle gestural interaction with output feedback being more accurate and quick-response. In the early stage, we considered Time-of-Flight (ToF) laser-ranging module (e.g. VL53L0X) as sensing technique but the resolution of which did not meet our expectation in such short distance (working range around the HMD).

Comfort. In the current design, HMD serves as the pivot of controller, which leads the applied force to distort the Field-of-View (FOV). From ergonomics perspective, we currently add straps crossing over user's chin to make TanGo stable and firm as the original functionality of helmet straps. In the future we plan to further add soft paddings to avoid the contact of straps and skin and mitigate the uncomfortableness. From the software side, we can develop the algorithms complementing the deformation of FOV based on the inertial sensors of smartphone.

Friction. The natural resistance is currently kind of large and disturbs the experience. We found the 3D-printer plays a critical role since if the structure is not match enough, the movement of sliding structure will be somewhat hindered; the materials also matter owing to the natural friction. We considered metal linear guideways before current design; however, it's more flexible to use 3D-printed components to balance size and weight and realize the structure of brake system. In the future, we believe when the high-level 3D-printer becomes approachable, this problem will be improved.

Fatigue. Due to the limitation of friction caused by the 3D-printing structure and electronics, the usability could now be an issue of TanGo. However, different from fatigue caused by the weight of devices of commercial products and prior research, the fatigue caused by TanGo is mainly because the resistive force. As the user feedback suggest, the weight of TanGo did not raise usability issue, instead, manipulating device full of force can sometimes destroy the user experience. We suggest that future works should pay much attention on designing kinesthetic force output while not exceeding the acceptance of users.

Interactions. TanGo requires users to raise their hands to input, which seems unfriendly and may cause fatigue if prolonged use; TanGo, however, also offer users chance to move their hands around in anytime and even rest without totally interrupting the immersion, which advantages the transition between bare-hand and tangible interaction, switch between virtual and real world, and unimanual and bimanual interaction. We argue that such flexibility of TanGo can also adapt the daily usage while the AR application only shows small parts of possible interactions. We believe this interaction space will be amplified in the future if hand gesture recognition, eye gaze detection or other sensing techniques are applied.

Lack of System Evaluation. In this paper, we primarily investigated qualitative feedback to obtain the preliminary user impression on TanGo and reveal various problems as above-mentioned. In the future work, we will evaluate the system in details, like the time period between profile changes, the rate to successfully identify profiles by users, the scores on each interaction and most importantly, the accecptable range of resistive force on TanGo device.

7.2 Comparison and Extension to current VR/AR

First, We want to reiterate that the main attention of this work is to explore the tangible interaction on HMD rather than competing with or replacing existing controllers. Instead, TanGo is rather a supplementary benefit to current VR accessories.

Applications. In first two proposed applications we aim to prove the adaptability of TanGo to current game scenarios, in which we hope that in the future HMD input and hand input can both be considered and complementary to each other to enhance variability of user experience. Moreover, we argue that TanGo has the potential to be an appropriate addition to AR scenario and collaborate with hand-tracking technologies to facilitate free-hand and tangible interaction, in which digital board game would be a good scene. From user feedback, we also find some values in real-word scenarios, like drone controller, as it's more intuitive in 3D space. In the future, small control widgets can also be added on the existing TanGo or other head-worn devices to enable always-available inputs.

Degree of Freedoms. Though current VR/AR input techniques are more spatially free and have higher freedoms than TanGo, we argue that the role of TanGo is to be an add-on to current VR/AR setup since no input modality is currently enabled on HMD. And in this paper, we have shown that TanGo can also be applied in such scenarios and hope future products or research can take HMD input as new supplementary. We encourage future works to investigate the interaction space of simultaneous HMD and hand input to maximize degree of freedoms.

8 CONCLUSION

In this paper, we present an active mechanical structure that enable totally 6 DoFs with each has 6 passive resistive force output profiles on off-the-shelf mobile HMD. Users can express multiple gesture inputs with output feedback tightly coupling. We carefully design our prototype, TanGo considering size, weight and stability. TanGo is an all-in-one structure aiming at providing a generic for rich VR input following haptic output. Lastly, we demonstrate TanGo's capability in several basic interactions in commercial games, where TanGo can adapt different scenarios and enhance the experience of gaming. We also apply TanGo to the AR scenarios that users can seamlessly manipulate physical objects while using TanGo as input entries to access virtual objects. Finally, we conduct a preliminary user study to collect feedback and then discuss the limitation and possible solutions. We believe TanGo can helpfully inspire future research in tangible interactions on HMD.

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