Geppetteau: Enabling haptic perceptions of virtual fluids in various vessel profiles using a string-driven haptic interface

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Figure 1: Geppetteau uses a string-based pulley system to dynamically relocate a vessel's center of gravity, producing haptic sensations of virtual fluids. Geppetteau can augment everyday vessel profiles, e.g., 4 example vessel shapes shown (left). Users at any physical setting (middle) can interact with virtual fluids in virtual settings (right).

ABSTRACT

What we feel from handling liquids in vessels produces unmistakably fluid tactile sensations. These stimulate essential perceptions in home, laboratory, or industrial contexts. Feeling fluid interactions from virtual fluids would similarly enrich experiences in virtual reality. We introduce Geppetteau, a novel string-driven weight shifting mechanism capable of providing perceivable tactile sensations of handling virtual liquids within a variety of vessel shapes. These mechanisms widen the range of augmentable shapes beyond the state-of-the-art of existing mechanical systems. In this work, Geppetteau is integrated into conical, spherical, cylindrical, and cuboid shaped vessels. Variations of these shapes are often used for fluid containers in our day-to-day. We studied the effectiveness of Geppetteau in simulating fine and coarse-grained tactile sensations of virtual liquids across three user studies. Participants found Geppetteau successful in providing congruent physical sensations of handling virtual liquids in a variety of physical vessel shapes and virtual liquid volumes and viscosities.

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CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Virtual reality*; Haptic devices.

KEYWORDS

Ungrounded haptic feedback; string-driven actuation; virtual reality; fluid dynamics

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1 INTRODUCTION

Every day, people interact with vessels filled with fluid, such as swirling water in water bottles, mixing acids together in beakers, or pouring oil out of an oil dispenser for cooking. As we manipulate vessels filled with liquids in our hands, we feel the liquid's material composition using our sense of touch and sight. For instance, gently swaying a glass of water reveals the nature of the liquid inside the glass; visually, and tactically. We see the clear liquid splash along the side of the glass. We feel the shifting weight of the liquid move from one side to another. The liquid movement creates force feedback where our fingers and palms grasp the bottle, cup, flask, or container. The sense of touch is a critical aspect of handling fluids in vessels, enabling several application areas, spanning from education to workforce upskilling/reskilling, to entertainment.

Experimental and commercially available haptic devices have expanded the space of possible interactions in virtual environments as researchers have explored methods beyond common virtual reality (VR) controllers to simulate specific tactile experiences that represent the physical world [9]. Haptic gloves [29] and world-grounded devices [18] have also been introduced towards enhanced tactile experience. While these devices aim to faithfully simulate the sensations of interacting with physical objects, other researchers have shown the effectiveness of sensory deception rooted in tactile illusions [23]. To this end, researchers present novel haptic devices that change the physical properties of a device to simulate tactile sensation of rigid objects [38], elastic objects [32], and liquids [33]. However, such systems are often fixed in size and shape. The number of virtual experiences are ever-expanding. There is a need for systems that are readily adaptable to the shapes and sizes of the various fluid vessels one would need for education, training, and other use cases. These devices should deliver haptic stimuli that is congruent with the visual stimuli, meaning that the haptic and visual stimuli should constitute as synchronous signals.

Feeling virtual fluid behavior inside custom shaped vessels opens up a multitude of new experiences in VR. For example, students would have the ability to experience virtual wet labs and can mix virtual fluids between beakers and Erlenmeyer flasks to cause chemical reactions. In workforce training scenarios, users could learn how to mix different paints or epoxies to get the right consistency and viscosity. In a farming game simulator, users might even water their virtual plants using different watering cans for different plants. These experiences need devices that have both the ability to actuate programmable virtual fluid behavior and to accommodate custom vessel containers.

To meet this need, we introduce Geppetteau, a novel haptic device that affords users with a wide range of tactile sensations related to handling virtual liquids in VR. Geppetteau enables the haptic sensation of virtual fluids in a variety of different vessel containers as Geppetteau's string-driven apparatus can accommodate a variety of vessel container shapes. Figure 1 illustrates an overview of the system. Geppetteau uses a string-driven apparatus inside of a swappable 3D printable vessel enclosure; as a user interacts with a vessel, the system actively pulls the location of an active mass inside the vessel (red sphere) to dynamically follow the center of gravity (CoG) of the simulated liquid in the vessel. We construct software interfaces to integrate Geppetteau vessels into virtual environments through game engines, e.g., Unity/Unreal, enabling the fluid simulation in such engines to drive the center of gravity of the simulated liquid, as shown in Figure 2.

A previous work SWISH [33] is a physical haptic interface that renders the haptic sensation of virtual fluids behavior in a large cylindrical bucket. It uses a rack and pinion system to actively shift a weight that moves with the virtual liquid's center of gravity giving the tactile sensation of virtual fluids in vessels. However, the rack-and-pinion actuation mechanism is not adaptable to different vessel shapes, outside of the SWISH bucket profile. Additionally, the size of the SWISH device is too large for smaller scale VR use cases. Given the string-driven nature of Geppetteau's weight-shifting mechanism, it can integrate inside a wider range of 3D-printed vessel shapes with convex hulls, including conical, cylindrical, spherical and cuboid shapes. Additionally, Geppetteau offers one-handed interactions with the vessel shapes as Geppetteau's size offers a significant 83.5% decrease in volume when comparing Geppetteau's cylindrical vessel to that of SWISH's.

Figure 2: Geppetteau provides sensations of handling virtual liquids in various vessels. (Left to Right) Conical, Cylindrical, Spherical, Cuboid

With our Geppetteau system, we present the following contributions:

- We designed a string-driven fluid center-of-gravity relocation apparatus. This system is capable of adapting to various vessel profiles.
- We developed an open-source digital-physical system to integrate the mechanism into handling virtual liquids in VR.
- We implemented a low-latency end-to-end integrated system that can be used in a variety of simulated environments with a variety of 3D-printable enclosures.
- We analyzed the efficacy of our Geppetteau interface with three embedded user studies.

Based on the user study results and testimonials, we found that the tactile sensations from the actively moving mass inside the vessels provided more haptic congruence to what was presented visually when compared to the baseline conditions of a static mass inside the vessels and a Vive controller. We found that our device provided the haptic sensation of feeling virtual fluids inside a vessel even when the users were not able to see the virtual fluids. The visual influence aided in strengthening the haptic illusion provided by our device. Lastly, we found that our device was able to provide tactile sensations of fluid behavior such as pouring from one vessel to another, chemical reactions such as bubbling and viscosity change, and simulating fluid behavior on different virtual planets with varying gravity. Our work suggests new directions and applications enriching the haptic experiences of fluid behavior and handling virtual fluids in VR.

2 RELATED WORK

Researchers have previously explored approaches to investigate the nuances of various interactions[6]. Haptic devices simulating force-feedback [8], texture [42], shape [13], and size [37] have been explored. Other haptic devices simulate the dynamic qualities of interacting with physical objects using change in the center of gravity (CoG) [44], inertia moment [36], resistance to wielding [45], and result of impact with other objects in the environment [22]. However, with the exception of a few haptic devices [33], most of these systems require a specific indirect point-of-touch on the object being manipulated. Our work shares conceptual similarities with these efforts and extends the knowledge in this domain.

2.1 Haptic Devices Simulating Tactile Sensation of Fluids

Providing haptic sensations of interacting with virtual fluids presents interesting challenges. Using mechanical add-ons for commercially available haptic devices, researchers developed world-grounded systems capable of providing high-fidelity haptic sensations of handling fluids in a variety of states [10][41][46]. Researchers explored open systems that change their characteristics by adding or removing physical matter, such as liquid [28] and changing air flow rate [17]. Although these systems provide high-fidelity haptic feedback, their mechanical complexity does not allow for straightforward integration into a wider range of physical vessel profiles to create intuitive user interfaces.

2.2 Passive Haptic Devices and Haptic Illusions

Researchers have shown the importance of passive haptics in enhancing the interaction with virtual environments [19]. Addressing the difficulties to scale the use of passive proxies researchers have also introduced haptic retargeting which enables the users to use the same physical proxy for multiple virtual objects [4]. While these devices enable the users to interact with virtual objects more intuitively they rely for the most part on visual dominance. To enhance the tactile experiences of haptic devices and building on tactile perception studies demonstrating that perceptual illusions that we experience in a real environment can also reappear in a virtual environment [16] and others such as dynamic touch [40]; researchers have explored ways to trick the sensory perception of holding [7][25], wielding [36], pull and push forces [2], grasping, and compliance [24]. Visual-tactile incongruence has also been explored [34] [30]. Our approach builds on these solutions and extends them to provide an intuitive and immediate point-of-touch of the haptic device to users.

2.3 Augmented Passive Devices

Researchers have investigated haptic devices that create illusions of objects with changing shapes and sizes, leveraging tactile size-weight illusion [1] for rigid objects [38, 44], elastic objects [39], and liquids[17]. Closely related to our approach, SWISH [33] provides a fluid vessel point-of-touch to users by enclosing a rack and pinion actuation mechanism inside a fixed-size large cylindrical vessel. While SWISH provides sensations of handling liquids by shifting its CoG, its rigid rack and pinion mechanism impedes its adaptability. Additionally, the nuance of liquid gently sloshing back and forth while handling a vessel gently does not always accompany a large shift in the CoG location.

2.4 String-Driven Actuation

String and cable-driven mechanisms have been shown to provide flexibility and accuracy comparable to rigid actuation mechanisms[35]. Commercially available systems such as Spidercam [15] can be deployed and implemented across the playing field of a sporting event. Haptic systems based on this mechanism have also been explored as well. Experimental devices providing haptic sensation in human scale have been designed to provide force feedback in VEs [20]. Also, world-grounded devices [26] and wearable devices [27] that provide resistive forces using tensioning strings [43] have been introduced as well. To the best of our knowledge, we believe we are the first to use this string-driven actuation mechanism to provide haptic sensation of virtual fluids inside vessels. Our system introduces a compliant string-driven system that can be enclosed inside a variety of vessel shape profiles including non-cylindrical ones. Furthermore, the inherent slack of a string suspended shifting mass in combination with gravity allows the mass to reach all areas of different vessel shapes in addition to capturing nuanced haptic sensations.

3 SYSTEM DESIGN

We aim to develop a set of low-cost, reusable, and adaptive actuation mechanisms that can imbue the shapes of everyday vessels with haptic perceptions of virtual fluids. Thus, in designing the Geppetteau we emphasized the following design considerations:

- *Haptic compliance for fluid sensations*, capable of providing small scale movements to match the nuances of interacting with liquids.
- *Adaptive design to suit familiar vessel shapes*, affording the ability to augment objects of various shapes to create an intuitive and immediate point-of-touch that is similar to daily experiences.
- *Recomposable software-hardware integration*, using readily accessible hardware and software components to empower the research community and hobbyists interested in experimenting with haptic devices in VR.

3.1 The Geppetteau System

In response to these needs, we design the Geppetteau system. Key to Geppetteau's actuation is its string-driven mechanism; Geppetteau uses 3 motors with spool shaft attachments to draw the active mass along axial (one motor at the top) and radial dimensions (two motors attached to a rotary base) while a fourth DC motor rotates the rotary base. The string-driven system leverages the inherent slack of the string in combination of gravity to have the active mass reach locations within the vessel. The slack in the string also enables users to feel nuanced movements of the virtual liquid.

Different shells can house the mechanism, allowing Geppetteau's weight-shifting system to actuate haptic sensations of vessels of different shapes and sizes. The string-driven nature of the system allows Geppetteau to integrate inside in a range of vessel shape profiles, including conical, cylindrical, spherical and cuboid shapes, augmented with Geppetteau's actuation mechanism. Altogether, this provides the force feedback sensations necessary to simulate virtual fluids in the handheld vessel.

Geppetteau integrates the physical apparatus into virtual environments through a set of digital components for sensing, tracking, and control. In our implementation, discussed in Section 4, Geppetteau tracks an augmented vessel in realtime using an HTC Vive Tracker [1], sends the 3D position and orientation of the vessel in the world space to the Unity Engine environment [2], simulates liquid properties using Obi Fluid [3], calculates the congruent relocation of the CoG, and sends position commands to the enclosed motors. The system actively pulls the location of the active mass inside the vessel to dynamically follow the center of gravity of the simulated virtual liquid, affording a tactile sensation that is congruent with the visual component of the virtual liquid.

3.1.1 Compliant Force Feedback of a Dynamic Fluid CoG. When a liquid is subjected to motion, it exerts a force in the opposite direction of the movement (i.e., Newton's third law of motion). For instance, when holding a glass of water and gently swaying it, we experience a reactive force equal to the force that we apply to move the glass. For the sake of simplicity, we evaluate the forces involved while handling Geppetteau using the principles of fluids in rigid-body motion [14]. Breaking down the motion into uniform linear acceleration (moving the vessel back and forth) and rotation about the vertical axis at an angular velocity ω (swirling the vessel), we observe the fluid reactions illustrated in Figure 3. In translation, the flexibility of active mass affords users a congruent reactive force that is expected of liquid vessels. While swirling the vessel, the angular velocity of the rotary base will match that of the user's, providing faithful angular momentum.

Geppetteau's active mass has the freedom to reach continuous locations inside various shaped vessels. Research has shown that faithful path-following of a weight-shifting system provides realistic sensations of handling simulated liquids in VR [33]. In our system, the location of CoG at any given time is faithful to the simulated CoG of liquid inside the virtual environment. Furthermore, due to the inherent flexibility of the string-suspended active mass our Geppetteau is capable of providing tactile sensations of a wider range of user actions including small movements that do not cause noticeable shifts in the CoG.

[1]https://www.vive.com/us/accessory/vive-tracker/
[2]https://unity.com/
[3]http://obi.virtualmethodstudio.com/

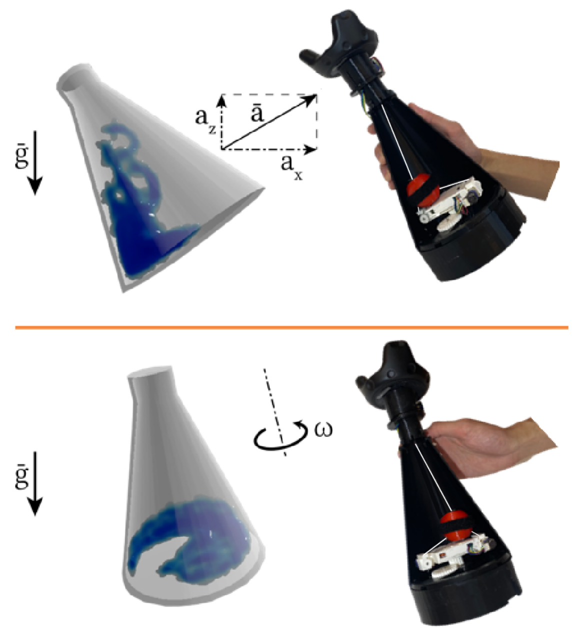

Figure 3: Geppetteau exerts forces related to linear acceleration (top) and rotation (bottom)

3.1.2 Adaptability to Familiar Non-Cylindrical Vessel. Unlike rack and pinion actuation systems, string-driven mechanisms provide wider flexibility in augmenting objects. In prior work, researchers introduced augmented cylindrical "SWISH" vessels [33] that leverage rigid actuation systems. However, these systems face structural challenges in adapting to non-cylindrical shapes. Researchers also provided systems with indirect point-of-touch [10] to overcome this challenge. However, using a handle to interact with liquid vessels only captures a subset of our daily interactions. To this end, we propose the use of nonrigid and flexible actuation mechanisms to be more suitable for augmenting objects (Figure 4).

While this work has four vessel profiles implemented, there are many applications that may benefit from custom shaped vessel profiles. The ability to swap shells allows for far more experiences with virtual fluids. The inherent flexibility of the string-suspended mass in tandem with gravity allows the mass to relocate inside different shaped vessels.

We designed our system to make swapping vessel profiles simple and easy. These custom shells can be 3D printed or manufactured with other materials. When changing vessel profiles, the only thing that needs to be swapped is the shell; the internal weight shifting mechanism remains unchanged. For example, these custom shells might be augmented by attaching materials with special textures such rubber or cloth. Grooves or bumps could also be printed directly into these custom shell shapes. Electrical heating pads could affix onto custom shells to provide temperature change for chemical reactions of virtual fluids.

Figure 4: Location of the active mass which corresponds to the location of CoG when a user performs the same action across four different shape shells. (From left to right) cylindrical, spherical, conical, cuboid

3.1.3 Composable Software-Hardware Integration into VR Experiences. Swapping out the virtual vessel using our software-hardware integration in VR experiences is designed to be as simple as swapping the physical vessel. If the physical vessel is swapped, then the virtual vessel should be swapped accordingly. A 3D file of the new vessel can be uploaded into the game engine and used in place of the previous virtual vessel. The virtual liquid can also be adjusted, dynamically changing its volume, viscosity and other properties. Further software-hardware integration details are expanded upon in the implementation section.

4 IMPLEMENTATION

In this section, we discuss the components of our implemented Geppetteau system to promote the reproducibility of our work. Figure 5 illustrates the abstracted system block diagram of the different components.

4.1 Vessel Hardware Design

We designed the vessel, transmission, motor enclosures and brackets with reproducibility and adaptability in mind. Figure 6 illustrates the physical components of our Geppetteau system. Most parts are produced using PLA material and printed with Ultimaker S5 3D printer [4]. The vessel shapes are 3D printed and only 8 screws are needed to swap from one shape to another. To track the position and orientation of the vessel, we use an HTC Vive Tracker mounted on top of the 3D printed vessel.

Geppetteau is a lightweight low-density system, which allows the active mass to contribute strongly to the relocation of the center of gravity. Without the 95g Vive tracker and its mount, the Conical Geppetteau weighs 480g; the Spherical weighs 540g; the Cylindrical weighs 560g; the Cuboid weighs 580g. The active mass, weighted with lead balls, amounts to 155g. To reduce the noise and rigid contact in the case of impact of the mass to the side of the wall, we added soft velcro to the enclosure of the active mass to provide softer padded contact to the inner side of the vessel.

To decrease the time for printing, the design of the enclosure is broken down into segments that are connected using either tongue and groove joints or M2.5 screws. The rotary base includes a large cavity for housing all the wires to avoid any entanglement. We designed cavities on the active mass enclosure to house a 3/4 in Neodymium disk magnet at the top and a 1/4 in cube magnet at the bottom. We use braided fishing line (10 lb, 0.14 mm) as the string to connect the active mass to the motors.

In our early experiments, we noticed that braided fishing line may get tangled or twisted due to line memory. Also, during these experiments, we exerted excessive forces on the system to evaluate its robustness. For the majority of times the system was able to complete the trajectory following. In rare cases (1 out of 15 tries) the string would get wrapped around the shaft of the motor instead of the pulley. We were able to observe this behavior using a vessel with half of the outer profile removed. To overcome this issue, we reduced the length of the exposed motor shaft by extending the width of the pulley and used commercially available fishing line conditioner on all strings to add rigidity. Additionally, we reduced our PID error $e(t)$ by reducing the PID computation intervals.

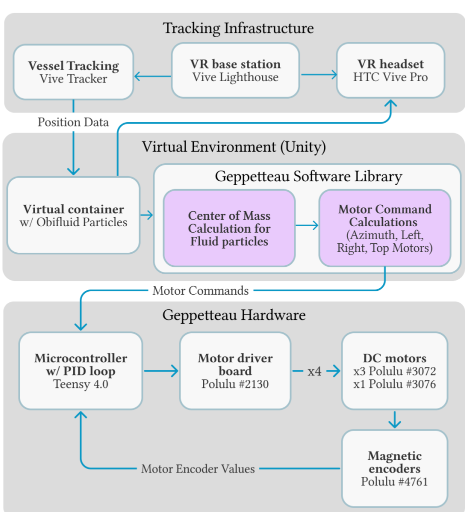

Figure 5: Geppetteau's system diagram

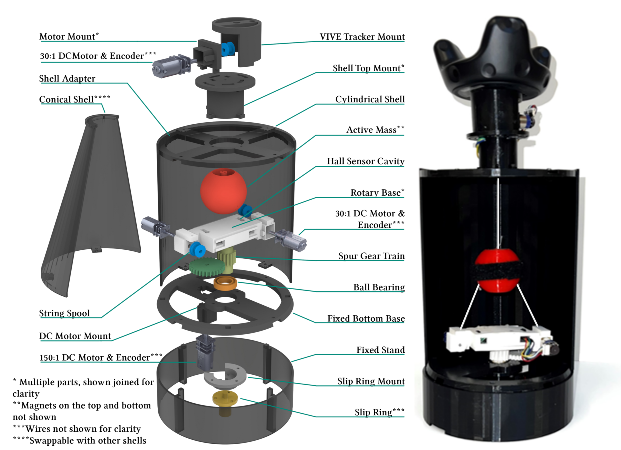

Figure 6: Exploded 3D CAD view of the Geppetteau system (Left). Assembled Geppetteau device with a cylindrical shell (Right).

[4] https://ultimaker.com/3d-printers/ultimaker-s3

4.2 Vessel Actuation, Motor control, and Referencing

We use four DC motors to actuate the active mass of Geppetteau to follow the CoG path of virtual liquid. Geppetteau uses 3 DC motors with spool shaft attachments to draw the active mass towards a desired location along axial (one motor at the top) and radial dimensions (two motors attached to a rotary base). At its base, a fourth motor rotates the rotary base sub-system providing actuation along the azimuth. As such, Geppetteau has 3 programmable degrees of freedom (DoF). However, our system also benefits from the slack in the strings, which enables it to rotate around the 3 axes (approx. 30°). This creates 3 additional passive DoFs (pitch, yaw, and roll).

For the rotary base sub-system, a Pololu 150:1 6V micro gearmotor [5] attached to the fixed bottom base provides actuation in the rotational axis. Rotation of the motor shaft is transmitted to the rotary base using a gear train. The power ratio between these gears is 1:2 (the first gear has 30 and the second 15 teeth) and their module is 0.9.

Two 30:1 6V micro gearmotor [6] motors actuate the active mass horizontally and another 30:1 micro gearmotor provides actuation in the vertical direction. The three motors used in the horizontal and vertical axes have a pulley with a radius of 3.5mm. For every action, there is a bias against a particular motor to actuate the CoG. For example, in the case of tilting a vessel, when the user tilts the vessel the horizontal motors will be under greater load than the vertical one due to the direction of gravity. However, these motors split the required torque to relocate the mass and the vertical motor only needs to wind the string and will not be under above normal working conditions. Our desktop power supply used in experiments was capable of providing 10 amps while the total required current for all motors to operate at maximum efficiency was 3.26 amps (per performance graphs). We carefully observed the change in the current during our initial experiments as well. The motors stayed close to their maximum efficiency based on the used current.

A 3D printed pulley connected to the shaft of each of these three motors holds the string. We use a PID position control system [3] to precisely wind/unwind the pulleys and ultimately relocate the active mass. Table 1 shows the PID coefficients that we calculated for our system, the sample time in milliseconds for computing the coefficients, and the frequency of the PWM signal.

Table 1: PID coefficients and computation interval (milliseconds)

	K_p	K_i	K_d	$t(ms)$	$f(kHz)$
Rotation	5.30	0.00	0.19	9	515.6
Horizontal	5.30	0.00	0.14	9	515.6
Vertical	5.30	0.00	0.14	9	515.6

For consistent relocation of the active mass, we implemented a homing system using 3 hall-effect sensors. When the embedded magnets reach a hall-effect sensor in a specific location it triggers execution of the next set of commands. Our Teensy 4.0 homing code executes the following set of commands: First, the active mass moves upward (vertical motor winding and horizontal motors unwinding). Second, the active mass goes all the way down for a specified number of motor ticks/steps that correspond to the length. Third, the right horizontal motor pulls the active mass toward itself while the left horizontal motor unwinds. Fourth, the left motor repeats this step. Lastly, both horizontal motors send the active mass to the center of the rotary base which corresponds to a specific amount of motor ticks/steps.

[5]https://www.pololu.com/product/3076

[6]https://www.pololu.com/product/3072

4.3 Software Implementation for Virtual Environment Integration

Our Geppetteau implementation runs using Unity. We use Obi Fluid to simulate real-time fluid dynamics, emulating properties such as viscosity, cohesion, and other fluid properties. Obi allows for fast performance of fluid simulations. According to the Obi documentation [7], the core physics solver of Obi runs completely on the CPU while rendering is done on the GPU. Additionally, Obi Fluid enables mixing of different colored fluids resulting in high visual fidelity for virtual chemical color changes.

While the fluid simulation uses Cartesian world-space coordinates in the virtual scene, Geppetteau translates the Cartesian world-space coordinates into a sequence of motor commands that maps to how the physical system actuates. The physical hardware allows for an active mass to actuate along the plane of the top, left and right motors, and around the rotational axis. Within the virtual space, the virtual vessel has empty game objects denoting the mapped positions of the virtual top, left and right motors which can also rotate together in the same manner as the physical system.

The virtual fluid is spawned in a virtual vessel identical to the physical vessel. The virtual vessel is a .obj file that maps to the same shape of the physical vessel. Geppetteau averages the particle positions to find the location of the CoG, computing its displacement relative to the vessel's origin. The distance between the position of the CoG of the particles and the position of the virtual top, left and right motors are calculated and translated into motor step commands for the physical top, left and right motors. These motors will then spin the spool of string based on the motor commands, spinning the spool to give more slack or shorten the amount of string available. The amount of slack available is based on the distance from the CoG of the virtual fluid to the positions of the virtual motors, which correspond to the physical motor positions. It is assumed that a virtual gravity acts on the virtual fluid and the physical gravity acts on the physical active mass.

The rotation of the three virtual motors along the azimuth of the vessel corresponds to the rotation of the CoG of the particles. The rotation angle is calculated through trigonometry using the position of the vessel's origin and the position of the CoG of the particles and then translated into azimuthal motor steps. Due to rotational symmetry, each CoG position has two equivalent motor positions so for every sequential position it may be better to choose one motor position over another. Geppetteau uses a minimax algorithm which prioritizes the position that requires fewer maximum motor steps for the azimuthal motor. The resulting position commands for the top, left, right, and azimuthal motors are sent to the Teensy as set point commands for the PID calculation.

[7]http://obi.virtualmethodstudio.com/faq.html

All of the properties to control the behavior of a fluid are adjustable by modifying Obi Fluid parameters, for example gravity, viscosity, partcile size, and particle amount. Based on the behavior of the virtual liquid, Geppetteau will respond to these changes and actuate the motors appropriately.

5 TECHNICAL EVALUATION

5.1 Omnidirectional Faithful Path-following

We saw that overall, Geppetteau was able to actuate the active weight to accurately follow the path of the CoG of the virtual liquid for different nominal actions across different shaped vessels. We measured the accuracy of the physical system in staying faithful to the virtual fluid's CoG in use case motions of swirling, swaying, shaking, and pouring across the different vessel profiles. We recorded the computed motor commands from Unity and achieved motor commands from the Geppetteau system. Since the motors spin the spools of string to pull the weight into position, the combination of the motor commands translate to the position of the active weight. The path error for each action represents the average of six trials and is shown in Table 2. On average across all the different shapes and across all the different actions, the azimuth motor had a 5.50% error, the left motor had a 2.25% error, the right motor had a 2.38% error, and the top motor had a 2.96% error. In Figure 7, we show the paths of the computed motor commands from Unity and the achieved motor commands by the motors with three trials of the "pour" action across the four vessel shapes. In Figure 8, we show an example plot for the "pour" action with the conical vessel. This figure illustrates the computed motor commands from Unity and the achieved motor commands by the motors.

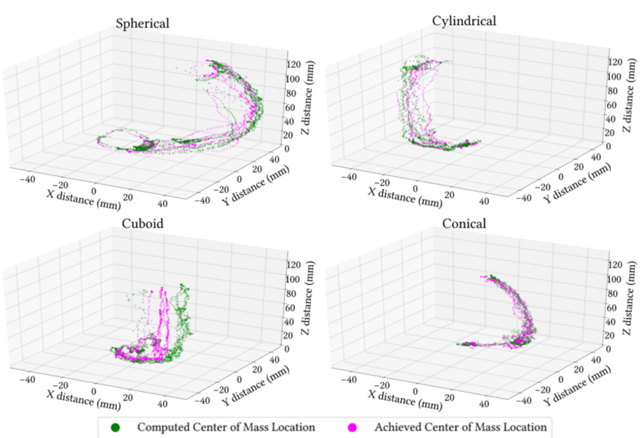

Figure 7: 3D Plots of 3 trials of "Pour" for the different shells.

5.2 Latency and Frame Rate

To understand the responsiveness of the Geppetteau system, we measured the latency of the motor commands throughout the software-hardware pipeline. To do so, we instrumented timestamps in our microcontroller and recorded the average latency across all of the different shapes for the 4 actions across all trials.

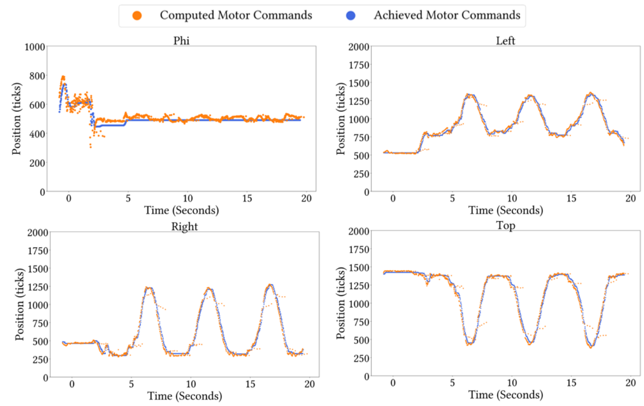

Figure 8: Motor command charts for conical "Pour" Action

These latency values are illustrated in Figure 9. Starting from the time the CoG is calculated to the time the motors arrive at the designated position, on average there was a latency of 11.8ms with a standard deviation of 7.5ms. The maximum latency was 65ms and the minimum amount of time was 0ms. In [12], users found the haptic and visual stimuli to be synchronous if the haptic feedback was presented less than 50ms after seeing the virtual object. Ergo, the haptic and visual stimuli for our Geppetteau system are perceptually synchronous in almost all situations. We also found that Geppetteau's Unity scene maintained a consistent 60 FPS, highlighting high real time visual fidelity.

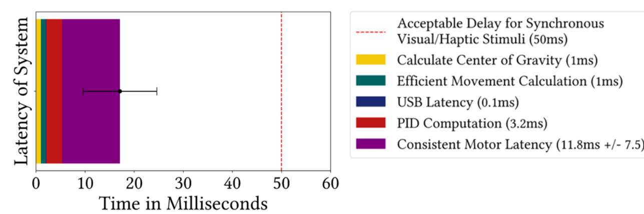

Figure 9: System latency next to latency for synchronous visual haptic feedback

5.3 Motor Speed and Power Consumption

The data sheet reports that at 6V drawing 1.5A assuming no load, the nominal maximum speed of the 30:1 motors is 1100 RPM and the nominal maximum speed of the 150:1 motor is 220 RPM. The maximum linear velocity in which the active mass can travel is 80.6 cm/s. The maximum angular velocity the 150:1 motor can actuate is 1320 degrees/s.

To understand the electrical characteristics of the Geppetteau device, we took measurements to calculate power usage while performing each of the four actions (swirl, sway, shake, pour) described in 6.1. We measured the power draw of the motors and associated motor controller hardware. This data informs future research into building a Geppetteau that is untethered and wireless, describing the minimum requirements of a battery that could power the device. We used a hall sensor to measure the current through our device.

Table 2: Path error between computed motor commands from Unity and achieved motor commands from Geppetteau system

	Cuboid				Cylindrical				Conical				Spherical			
Action	Azimuth	Left	Right	Top	Azimuth	Left	Right	Top	Azimuth	Left	Right	Top	Azimuth	Left	Right	Top
Swirl	7.14%	1.54%	1.14%	1.17%	6.71%	1.71%	1.64%	2.01%	6.70%	1.47%	1.31%	1.29%	7.46%	1.90%	2.03%	2.77%
Sway	4.38%	1.62%	1.14%	1.12%	4.63%	2.18%	2.09%	2.50%	6.32%	1.95%	2.29%	2.16%	5.70%	2.38%	2.60%	2.34%
Shake	4.06%	2.06%	2.52%	2.76%	5.50%	4.41%	4.09%	6.99%	4.47%	3.32%	3.67%	5.68%	6.10%	3.07%	3.87%	5.70%
Pour	4.29%	2.10%	2.49%	2.78%	3.22%	2.32%	2.55%	2.66%	5.13%	1.76%	2.04%	2.10%	6.18%	2.21%	2.67%	3.21%
Average	4.97%	1.83%	1.82%	1.96%	5.02%	2.66%	2.58%	3.54%	5.66%	2.13%	2.33%	2.81%	6.36%	2.39	2.79%	3.51%

The measurement period started once the active device was picked up, and ended once the device was placed down - between 30 to 60 seconds for each of the four actions.

Table 3: Average current and power table

	Average current draw I_{avg} (+/- 2%) Amps	Average power draw P_{avg} (+/- 2%) Watts
Shake	1.03 A	6.20 W
Pour	0.84 A	5.04 W
Sway	0.77 A	4.60 W
Swirl	0.72 A	4.33 W
Average	0.84 A	5.04 W

The data in Table 3 demonstrates that the device draws more power relative to how much the device is agitated. The shake action draws the most power, which we believe is because it drives 3 of the motors in rapid succession (the two horizontal and one vertical motor) to follow the fluid that is being shaken up and down. Meanwhile, we believe the swirl action draws the least power because it relies on just the rotational motor to match the fluid's center of gravity.

6 PERCEPTUAL USER STUDIES

We conducted three user studies to evaluate how well Geppetteau can provide congruent physical sensations of handling virtual fluids in a variety of physical vessel shapes and virtual liquid volumes and viscosities. In user study ①, we investigated the effect of Geppetteau's haptic sensations on the user experience compared to two baselines. We compared an active weight Geppetteau system to two baselines of no haptic feedback (a Vive controller, and a Geppetteau system with an unmoving static weight). The virtual fluid was visible in each condition. In user study ②, we evaluated the role visual dominance played on the user's perceived haptic sensations from the active weight Geppetteau system across the four vessel shapes. In user study ③, we evaluated the haptic sensations Geppetteau provided for various fluid behaviors. We developed an immersive experience where users could interact with two Geppetteau systems to create different fluid behaviors in virtual environments with different gravities. In our studies, the users wore a HTC Vive headset and noise canceling earmuffs as we intentionally wanted to explore the visual and haptic congruence. The users were seated while performing the user studies.

Study ① was conducted with three conditions: 1) Vive controller, 2) Static Geppetteau system with a static mass, and 3) Normal Geppetteau system with an actively moving mass. 5 participants were randomly assigned to each condition, for a total of 15 participants. This study took roughly 30 to 40 minutes. 11 participants self-identified as males and 4 as females. Participant ages ranged from 20-26. 12 participants had used VR headsets before. The participants received a $15 Starbucks giftcard as compensation.

Study ② and ③ was conducted with a different set of participants. 32 participants went through ② and then ③ - taking roughly an hour total. We used study 2 to familiarize users with the devices before going into the embedded space adventure of study 3. 17 participants self-identified as male, 14 self-identified as female, and one preferred not to say. Participants ages ranged from 18-34. 27 of the participants had previous experience in VR. The participants received a $20 Starbucks giftcard as compensation. All studies were reviewed and approved by the institutional review board.

6.1 User Study 1: Geppetteau System Compared With Baseline

We wanted to understand how the weight shifting or lack thereof impacted the user's experience. Our goal for this study was to compare an active weight Geppetteau system with the Vive controller and static weight Geppetteau system baselines. The controller is the default device people use to interact with virtual objects. The static weight system represents a simple physical proxy. For each condition (Vive controller, static weight Geppetteau and active weight Geppetteau), users were asked to perform four actions three times - sway (side to side), shake (up and down), swirl (around the vertical axis), and pour across each different vessel profile - conical, spherical, cylindrical, and cuboid. For every user, the actions were randomized using a balanced Latin square, and the order of the devices were randomized through a random sequence.

After each action was performed, the users answered three modified VRUSE [21] questions Q1 "The tactile response to my interactions felt accurate" (Modified VRUSE 10), Q2 "The overall system behaved in a manner that I expected" (VRUSE 48), and Q3 "I had the right level of control over the simulation" (VRUSE 68) within the VR environment.

We also had the users go through a cognitive walk through during the experience to gain insight into what they were seeing and feeling. After each set of four actions per vessel, we asked a question. Users verbalized their responses, which we transcribed while they were in the experience. There were four questions we asked each user. 1) Describe your experience with the device. 2) Does what you're seeing match with what you are feeling? 3) How did this experience compare to your experience with day to day liquids? and 4) Do you have any more comments?

Results. User responses from the cognitive walkthrough demonstrated a need for actively shifting weight inside the vessel for congruent haptic sensations of handling moving liquid. While users in the active condition reported adequate feedback from the vessel, users in both the controller and static condition shared that they did not feel any tactile feedback where they expected to.

For the controller condition, all 5 users remarked that they expected to feel some sort of vibration but they did not feel any haptic feedback from the controllers. Two of the users shared that they wanted to feel a shift in weight when interacting with the controller.

User 2, controller condition: *"The way the liquid moved upwards very easily, I expected some type of force when the liquid came down."*

User 5, controller condition: *"I don't feel any vibrations or anything. I just see it happening. I feel like when I pour water, the weight should have distributed downwards."*

These quotes show that the controllers did not provide the tactile feedback the users were looking for.

For the static condition, all 5 users remarked that they did not receive any tactile response from the vessels they held.

User 3, static condition: *"In terms of sight it looks pretty precise. As what a liquid would feel, the touch aspect was a little muted."*

User 4, static condition: *"I did not feel much at all. There was not much [visual] mismatch but there was not much feeling. I expected some kind of force feedback."*

User 5, static condition: *"I didn't feel much of a water movement, it kind of just felt like holding up a controller. There is a lack of 'oomph' when I'm tilting and moving it around compared to what actual water bottles feel like. When I pick it up and all the movement inside and the way the water looks while moving looks really good. I just don't feel much of a haptic response."*

User 1 and 2 of the static condition simple stated *"Did not feel tactile feedback"*. While users remarked that the visual aspect was compelling, the overall consensus is that the tactile sensation of the moving liquid was missing.

For the active condition all 5 users remarked that the tactile sensation of the shifting weight matched with what they saw visually.

User 2, active condition: *"It acts like water does with gravity. It flows to the lowest point. It's not like super quick or super slow, it's just like that perfect speed."*

User 4, active condition: *"I thought it was fun. The idea is innovative. I like to watch the water fill up. I like how it feels."*

User 5, active condition: *"Visually I see some type of container with what looks like a blue liquid inside and it seems to move as I would expect a liquid to. The center of mass of the liquid seems to follow the visual cues, so if it's all on one side, the device seems heavier on that one side. It was very convincing. It was a very good experience for the liquid simulation sometimes, but sometimes there were discontinuities ... which detracts from the overall experience. It breaks the immersion."*

Users 1 and 3 of the active condition stated "Yes, what I saw matched with what I'm feeling". What detracted from their experience was the sensitivity of the active weight, as they experienced some jitter movement which made the tactile experience feel unnatural at times.

Across all 15 users, 5 users commented on the visual aspect of the virtual liquid itself and compared it to a jello substance or a collection of pellets. The users imagined the use cases in classrooms for chemistry, physics labs, and training use cases.

We analyzed the answers to both the three VRUSE questions as well as the user responses. The means and standard deviations of the scores are shown in Fig 10. In the cognitive walk through responses, we found that users did not find controllers to provide congruent experiences. The users reported that the static condition lacked tactile feedback but looked good visually. Users reported that the actively moving weight provided a more congruent experience compared to the static weight; however some jitter movement in the active weight condition detracted from their ratings. These findings seem to be reflected in the VRUSE questions as well.

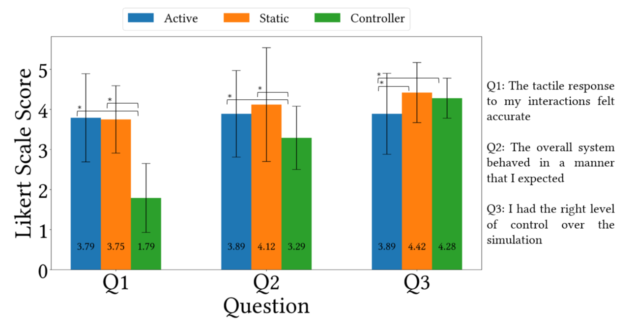

Figure 10: VRUSE question results for Active, Static and Controller conditions. Our findings show that users did not find controllers to provide congruent experiences. User's qualitative responses give insight into the active and static score differences. Significant comparisons have asterisk symbol denoted.

For each question, we conducted pairwise comparisons for the three conditions using Tukey's HSD test to see whether the differences in the means where statistically significant. The three pairwise comparisons were Static vs Active; Static vs Controller; Active vs Controller.

For the Q1, we found statistical significance ($p < 0.05$) for Static vs Controller (Q=18.66, p=0); Active vs Controller (Q=19.01,p=0). For Q2 we found statistical significance for Static vs Controller (Q=18.66, p=0); Active vs Controller (Q=19.01,p=0). For Q3 we found statistical significance Static vs Active (Q=6.18, p=0.00006), and Active vs Controller (Q=4.45, p=0.00522). The significance is denoted by asterisks in Figure10.

From this study, we gained more insight into how the ball moved when the virtual liquid was acting irregularly. Through trial and error testing, we learned how to better tune the virtual liquid parameters to account for device sensitivity to improve the congruence of the visual and the tactile sensations.

6.2 User Study 2: Exploring the Impact of Visual Dominance with Geppetteau Across Multiple Vessels

In this study, we sought to understand how well our active weight Geppetteau system could replicate haptic sensations of virtual fluids across different vessel profiles and how visual dominance influenced the tactile sensations perceived by the user. We hypothesized (**H1**) that the haptic feedback provided by our Geppetteau system would be rated highly in terms of accuracy, overall system matching expectations and level of control provided across different vessel profiles. We further hypothesized (**H2**) that the performance of our Geppetteau system would not be significantly different when the visual component was decoupled from the haptic sensations.

To test (**H1**), the users performed the four actions across the four vessels answering the same 3 questions as from study 1. For every user, the actions were randomized using a balanced Latin square, and the order of the devices were randomized through a random sequence. After the users completed all the actions for the four vessel profiles, they were asked to rate the functionality (VRUSE 7), consistency (Modified VRUSE 55), usability (VRUSE 100) of the system and their overall sense of presence during the experience(VRUSE 89). For the VRUSE questions, users answered on a 5-point Likert scale (1 - strongly disagree, 5 - strongly agree).

To test (**H2**), we had 32 users randomly assigned into two groups of 16 users. One group could see the virtual fluid in a clear virtual vessel, while the other group was told that there was a virtual fluid inside of an opaque black virtual vessel. In both groups, users would perform the four actions across the four vessels and feel the weight shift of the virtual liquid inside the vessels.

Figure 11: Virtual fluid is not visible in black container (Left), Virtual fluid is visible (Right)

Results. The results of the user study are shown below in Figure 12, Figure 13, and Figure 14. The mean ratings to the VRUSE questions are summarized in these results. In comparing the black vessel and clear vessel conditions, it was shown the visual aspect of seeing the virtual liquid does have a significant difference, contrary to our expectation. We conducted one-way ANOVA comparisons between each question for the black and clear vessel conditions - for example Q1 of black vessel condition compared with Q1 of the clear vessel condition. The probability values are displayed in the bars of the figures. The significant results ($p < 0.05$) have the bars outlined black as well as an asterisk symbol noted. In Figure 12, we compare the scores of black and clear vessel conditions of each vessel profile averaged across actions. In Figure 13, we compare the scores of the black and clear vessel conditions of each actions averaged across vessel profiles.

The results of the black and clear conditions show a statistical significant difference between the user ratings. The visual impact of seeing the virtual fluid in correspondence with the physical sensation influences the user experience. Nonetheless the black vessel condition ratings were still all positive with all the scores for Q1, Q2 and Q3 rated above 3 across all the vessel profiles and across all the actions. These results demonstrate that visual congruence improves the effect of the sensations related to fluids.

Users from both the black vessel condition and clear vessel conditions were asked to rate Geppetteau's performance in functionality, consistency usability, and providing presence. Based off the one-way ANOVA probability calculations, no significance differences were observed. Geppetteau performed equally as well for both conditions as shown in Figure 14. These results offer support for **H1** and **H2**.

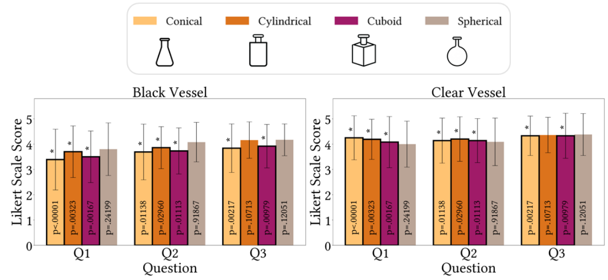

Figure 12: Black and Clear vessel comparisons for each vessel profile. Scores averaged across all actions. Significant results between black and clear vessel conditions are outlined black and have asterisk symbol denoted.

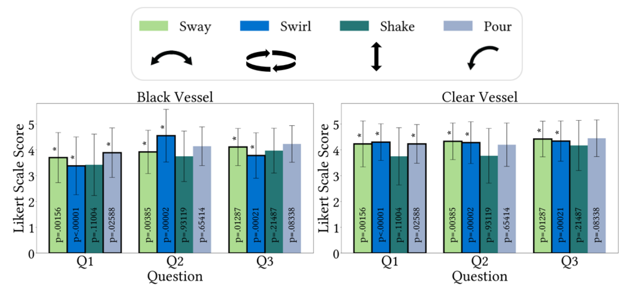

Figure 13: Black and Clear vessel comparisons for each actions. Scores averaged across all vessel profiles. Significant results between black and clear vessel conditions are outlined black and have asterisk symbol denoted.

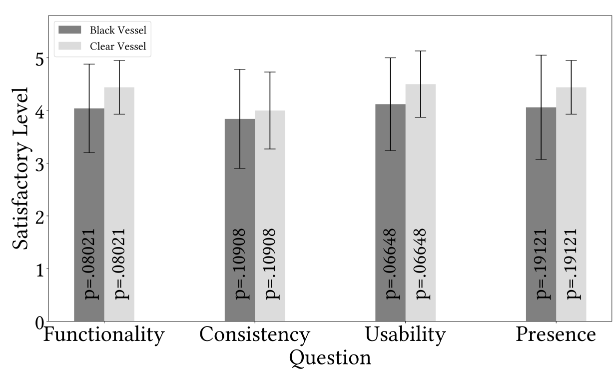

Figure 14: VRUSE question results for system functionality, consistency, usability, and presence answers

6.3 User Study 3: Fluid Behavior in an Immersive Experience

We hypothesized (**H3**) that the Geppetteau system could produce haptic sensations of various fluid behaviors thus enhancing practical and imagined applications of handling virtual fluids. We developed an immersive space adventure shown in Figure 15 to demonstrate the different liquid interactions provided by our Geppetteau system. The users wore an HTC Vive headset and were able to interact with two Geppetteau devices: the conical vessel and the cylindrical vessel.

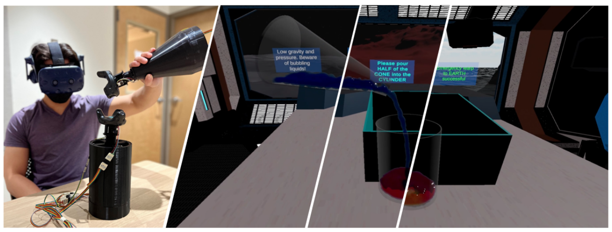

Figure 15: (Left to Right) User pouring the two Geppetteau Systems, Planet X, Planet Y, Earth

The user is on a spaceship flying back to Earth. The ship is hit by an asteroid and is forced to crash land on Planet X, which has a gravity of -4.5 $\frac{m}{s^2}$. The user needs to help mix new fuel for the ship. The user pours virtual chemicals from a conical vessel into a cylindrical beaker to make new fuel. On planet X, the chemical reaction is modeled after bubbling in which the virtual liquid bounces up and down. This gives enough fuel for the ship to travel to Planet Y with a gravity of -16.5 $\frac{m}{s^2}$, and the user once again needs to make more fuel in order to return to earth. The user pours from chemicals from the conical vessel into the cylindrical vessel and this time on Planet Y the reaction was modeled after viscosity change where the fluids gradually became more viscous as they were mixed. The entire viscosity change takes 4 seconds total. The fluid starts with the viscosity parameter of the Obi fluid at 1.0 and then goes to 1.5, 2.5, 3.5, and finally settles at 4.5 in 1 second intervals. After the ship makes it back on Earth with a gravity of -9.8 $\frac{m}{s^2}$, the user is asked to mix fuel in order to prepare for the next adventure. Once the users completed this experience they were asked to complete a questionnaire with VRUSE [21], SIM-TLX [11] and testimonial questions which asked about the chemical reactions, pouring, overall experience, and potential applications of our device.

Results. Participants were excited about our Geppetteau device and how they were able to create chemical reactions with the virtual fluids through their space adventure and shared about their experience in our post-study questionnaire. User 2 shares "The most engaging part was the chemical reactions, the sensations felt when pouring and mixing the liquids made the experience more realistic." When pouring the virtual fluid from the conical into the cylindrical vessel, user 23 notes "it is accurate and congruency to the experience in the real experimental context. Both tactic and control feelings are good." User 15 shares that "I got a bit excited every time that it asked me to either swish around the fluids or pour them, as I loved being able to feel them [liquid] move around the container. I especially enjoyed feeling the device get lighter as I poured it, and really enjoyed no longer feeling the liquid after I poured it all out."

Table 4 shows that users rated our Geppetteau system's fluid interactions, chemical reactions and gravity changes from the virtual environment well.

Table 4: VRUSE questions asked after the space adventure

Type of Question	Statement	Mean +/- Std
Modified VRUSE 80	I felt that the device enhanced my immersion in the virtual environment	4.41 +/- 0.66
Modified VRUSE 10	The device response to my interactions felt accurate	3.78 +/- 0.87
Modified VRUSE 62	Handling the Geppetteau system provided close to real sensations of the fluid behavior	3.88 +/- 0.80
Modified VRUSE 13	The pouring from one device into another felt accurate	4.06 +/- 0.76
Modified VRUSE 48	The first reaction sensation from the device matched what I saw in VR	4.00 +/- 0.88
Short Answer	What reaction do you think this was?	N/A
Modified VRUSE 48	The second reaction from the device matched what I saw in VR	4.06 +/- 0.76
Short Answer	What reaction do you think this was?	N/A
Modified VRUSE 13	The gravity differences on the different virtual planets for the virtual liquids felt noticeable from the device	3.84 +/- 1.14

Rather than explicitly tell the user what the reactions were, we had users guess what the reactions were in short-answer form. For the first reaction, 18 users out of the 32 answered either bubbling or with phrases similar to bubbling such as vibrating, moving up/down, or shaking. User 2 shares "The bubbling of the first reaction felt pretty realistic, and it definitely made the experience more immersive." On the other hand, 4 users didn't feel anything. 1 user did not remember. 9 users identified a reaction but did not include anything related to bubbling (e.g., color change, heavier, or saw liquid move on its own but did not specify a connection to bubbling).

For the second reaction, 12 users out of the 32 answered either viscosity change or with phrases associated with a higher viscosity (increased resistance, slower, heavier, calmer). User 27 mentions, "smooth texture but it felt more like it moved in clumps which reminded me of how jello felt and moved around like." 7 users thought the reaction was bubbling. This might have happened because when the users poured from the conical to the cylindrical shell, they accidentally bumped the Vive pucks together which jolted the virtual fluids inside up and down. The rest of the users either did not notice a change or felt heaviness after the reaction but attributed the heaviness to the new environment.

Table 5: SIM-TLX questions asked after the space adventure

Type of Question	Statement	Raw TLX Score (0-100) Mean +/- Std
Mental demands	How mentally fatiguing was the task?	9.68 +/- 15.08
Task complexity	How complex was the task?	6.25 +/- 8.89
Distraction	How distracting was the task environment?	9.375 +/- 13.24
Perceptual strain	How uncomfortable/irritating were the visual and tactile aspects of the task?	9.53 +/- 11.24
Presence	How immersed/present did you feel in the task?	65 +/- 27.15

The SIM-TLX scores from Table 5 revealed that our space adventure was not mentally fatiguing, complex, distracting or uncomfortable. However, it did show us that the overall presence and immersion of our system can be improved.

This study also revealed opportunities for us to improve future iterations of our device. In the testimonials, some users mentioned that their suspension of disbelief was interrupted by a few factors.

Wires getting in the way of the user's activities were a hindrance. User 18 mentions that "wire on the object affects the movement."

The ambient audio playing in the scene did not fully drown out the mechanical noises enough. User 27 comments that "I think audio could be an improvement to the experience to drown out the mechanical noises from the device which made it seem less realistic."

Occasionally there was unexpected fluid behavior which in turn caused unexpected haptic sensations. User 17 mentions the occasional tunneling of the Obi Fluid through the container where the "only issue is liquid seems to falling out of the walls." User 22 also shares that "The biggest improvement would be for the containers of liquid to stop shaking and spilling when they are not being moved or are only being moved gently."

7 DISCUSSION

Active Weight Geppetteau vs Controller and Static Weight Baselines. From study 1, we found that the Vive controller and static weight physical proxy were insufficient in providing the tactile experience of handling virtual fluids in vessels. To this end, this demonstrates a need for providing congruent haptic sensations to the moving virtual fluids. An actively shifting weight inside the vessel is a way to achieve this goal. The lack of visual and haptic congruence in the case of the Vive controller was reflected in the user ratings and feedback. While the static and active Geppetteau conditions had similar results for the likert scale scores; the users in the static condition highlighted missing force feedback. The users were expecting some shift in weight when handling the device, but felt nothing. Meanwhile, the users in the active weight condition thought that the tactile sensations from the shifting weight matched with what they saw from the virtual fluid. However, they did mention that feeling occasional jitter movement from the weight negatively impacted their experience. The virtual fluid parameters needs to be tuned appropriately to account for the sensitivity and to remove jitter. Overly sensitive Vive trackers, or loss of tracking may have also contributed to the jitter.

Visual and Haptic Congruence. We found from study 2 that our device was able to provide the haptic sensation of feeling virtual liquids inside a vessel even when users couldn't see the virtual fluids. When users saw the virtual fluid in correspondence with the tactile sensations, the haptic illusion was strengthened. We believe that different types of visual illusions could be used while the user is handling Geppetteau to influence the user's perception of weight[31] and the user's perception of size[5]. These visual and haptic illusion combinations can work towards opening the design space of what's possible with Geppetteau.

Fluid Behavior. In our immersive space adventure, users who were able to feel the chemical reactions responded positively to the experience. Some users were unable to detect the fluid behavior change or misclassified the fluid behavior. We believe that adding more guidance cues could help the users really narrow what they are feeling and experience the intended haptic sensations. A more congruent mapping between the physical and virtual, for example adding Vive trackers in the virtual scene, would also give users a better spatial awareness and reduce unintended bumps.

Range of Liquid Rendering. Our Geppetteau system uses a string-driven actuation system to move an active weight to the position of the CoG of the virtual fluid. How the CoG of the virtual fluid moves is determined by the Obi Fluid parameters. There are a couple special cases of no liquid and completely full liquid. In these situations, we can keep the active weight suspended in a position inside the vessel similar to a static weight scenario. Where this position is and the resulting visual-haptic congruence with regards to weight perception can be an area of future exploration.

There are cases when the string system may fail to render congruent haptic sensations for the virtual fluid. For example, if the virtual liquid is of high viscosity and there is too much slack available, then slight shaking of the device would result in the active weight moving when the high viscosity virtual fluid does not. Another example is when the strings are too twisted and tangled as the motors are no longer able to move the active weight. An example scenario is if the active weight is in a position which results in high slack, and the user jolts the device quickly making the string twisted or tangled. In our experience we found that with a few twists of the bottom two strings, the motors were able to untwist the strings when tightening. However, if there are too many twists or tangles, the motors can no longer move the active weight to the proper position. Our Geppetteau system can not render congruent haptic sensations of virtual fluids in zero gravity virtual scenarios. In this case, the movement of the active weight is constrained to the area where the motors can pull it but can not reach all areas in the vessel.

8 LIMITATIONS AND FUTURE WORK

Our experimentation and evaluation provided an insight into areas of improvement in the future.

8.1 Quantification of the System

We experientially evaluated the robustness of our Geppetteau's mechanical actuation mechanism. During our initial testing and user study, our system withstood rapid and violent actions. However, to demonstrate the complete working conditions of the system we need to quantify how every action affects the precision of the system. In the future work, we plan to use an automatic/robotic apparatus to shake the vessel with a specified and consistent force to be able to derive precise mechanical response of the actuation mechanism.

We also recognize that measuring the position of the mass with a motion tracking system may provide more accurate response compared to measuring the position from the motor encoders. As future work, we plan to look into and measure our active mass position with these motion tracking systems e.g. an OptiTrack system.

8.2 Physical Design Implications

Our current implementation of the Geppetteau actively relocates a fixed sized active mass. To scale this design to larger vessels there may be a need for a larger active mass to create perceivable tactile sensations of weight-shifting. To this end, a different set of motors may be required if the size of the active mass changes. The choice of motors depend on achieving higher speed while having reasonable torque. Additionally, some users remarked that they could still hear the motor actuation. Careful study of performance graphs for DC motors will guide designers in choosing the right motors for both torque and quietness.

As mentioned earlier, our current implementation of Geppetteau uses the HTC Vive infrastructure. Small bumps or loss of tracking using the trackers result in unexpected behavior within the fluid simulation. We plan to look into physically streamlined tracking systems that are more robust to small bumps and occlusion.

8.3 Virtual Fluid Limitations

Obi Fluid is a complex system which opens up many fluid parameters to adjust for simulating real-time fluid dynamics. Fine tuning the fluid parameters into the desired fluid behavior is an iterative process through trial and error. Occasionally there may be unexpected fluid behavior, such as virtual liquid passing through the virtual container walls. The physical system follows the center of mass of the virtual fluid - with a volatile virtual liquid, the physical active mass will follow. Volatility of the virtual fluid may be exacerbated by loss of tracking or overly sensitive Vive trackers. We plan to continue on iterating on the fluid parameters and find better parameters which result in more stable virtual fluid. We also plan to explore alternative tracking solutions.

8.4 Future Explorations

We want to expand the virtual experiences possible with the Geppetteau device - chemistry (e.g. expanding the experiments possible), physics (e.g. liquids in space), biology (e.g. transporting moving small animals where the small animals act as the active mass rather than liquid). We would like to explore the possibilities shared by the users in the testimonials after the space adventure - users shared that they imagined this device used in virtual cooking, science experiments, and physical therapy scenarios. We would also like to explore how these experiences change with special vessel profiles such as vessel profiles with handles or vessel profiles which can provide tactile feedback such as vibrations or temperature change. Exploring these additional tactile capabilities in combination with a shifting active mass is an interesting avenue for future work in studying the haptic sensations of virtual fluids.

9 CONCLUSION

With the advancements and the increasing interest in the VR technology, there is vast opportunity for research and development in the area of haptics for virtual environments. Existing literature afford us a wealth of information on ways to provide meaningful tactile sensations to VR users. However, there exists a gap of knowledge in providing ways to simulate sensations that users find close to their daily experiences of handling fluids. We envision the design of adaptive, scalable, and effective actuation mechanisms capable of augmenting everyday objects of all vessel profiles.

In this paper we introduced Geppetteau, a novel string-driven mechanism capable of providing nuanced sensations of handling virtual liquids in VR for different vessel profiles. We evaluated the response time, faithful CoG path following, and power consumption of Geppetteau.Geppetteau is both highly accurate and gives users a perceived real time feedback with an overall of 17 milliseconds of end-to-end delay. Using the built-in features of Obi Fluid in Unity, we created simulated scenarios providing users an intuitive way of performing familiar actions with the four vessels. Furthermore, we developed and tested an immersive context of application for our Geppetteau system in which users followed a set of instructions including adding virtual chemical agents to change virtual liquid state and viscosity in an imaginary space setting of various planets. Overall, users reported positive reactions to our system. We hope that our design and implementation of Geppetteau influences and inspires future research and development of haptic sensations of virtual fluids in vessels.

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