A Multi-Modal Auditory-Visual-Tactile e-Learning Framework*

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Abstract. With a high number of countries closing learning institutions due to the restrictions in response to the COVID-19 pandemic, over 80% of the world's students was not attending school. As a response to this challenge, many educational institutions are increasing their efforts to utilise various educational technologies and provide remote learning opportunities. One of the biggest drawbacks of the majority of these existing solutions is limited support for hands-on laboratory work and practical experiences. This is especially relevant to science, technology, engineering, and mathematics (STEM) departments, which must continuously develop their laboratories and pedagogical tools to provide their students with effective study plans. To facilitate a safe, digital access to laboratories, a novel haptic-enabled framework for hands-on e-Learning is introduced in this work. The framework enables a fully-immersive tactile, auditory, and visual experience. This is achieved by combining virtual reality (VR) tools, with a novel wearable haptic device, which is designed by augmenting a low-cost commercial off-the-shelf (COTS) controller with vibrotactile actuators. For this purpose, the Unity game engine and the Valve Knuckles EV3 controllers are adopted. To demonstrate the potential of the proposed framework, a human subject study is presented. Results suggest that the proposed haptic-enabled framework improves the student engagement and illusion of presence.

Keywords: E-learning · VR · haptics.

1 Introduction

E-Learning courses and contents have been dramatically boosted by the Covid-19 pandemic although many universities and higher education institutions were already starting providing on-line contents. Most probably, all the experiences gained during the period of mobility restrictions will represent a step change in

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the world of learning, with effects that may potentially rest also when the sanitary emergency will be finished. E-Learning brings several possibilities in terms of interaction for the students, enlargement of possible users and design of specific contents [3]. However, there are many aspects of a "in presence" lecturing that cannot be delivered "at home". Among all, physically attending a lecture is an experience involving all the human senses beside the auditory and visual channels typically used for e-Learning. As an example, several medicine classes are held in practical labs, where students not only listen to the teacher, but can also physically interact with dummy reproduction of organs or ex-vivo experiments. In these examples, the sense of touch plays a fundamental role and is at the bases of the whole learning process. Several other examples can be identified in other disciplines with a similar predominant role of tactile experiences. This is especially true for science, technology, engineering, and mathematics (STEM) education. In the last two decades, the field of Haptics has introduced a possible digitisation of the sense of touch [9]. Starting from complex and cumbersome desktop haptic interfaces, in the last few years many research groups have proposed wearable haptic interfaces, which enable a multi contact interaction with virtual or remote objects [16, 19]. This opens up to the opportunity of a new generation of e-Learning contents that includes tactile experience. The main roadblock toward the spreading of this technology is the current cost or complexity of the proposed solutions, that must also include a reliable hand tracking system [4]. To achieve a possible large spread of solutions allowing the developments of tactile contents, it is necessary to develop systems with a reduced cost by using commercially available off-the-shelf (COTS) components.

In this perspective, our research group earlier presented a low-cost platform for a fully immersive haptic, audio, and visual experience to allow researchers for including haptic capabilities in a more adaptable, interactive, and transparent manner to their applications [23]. This is made feasible by a pair of haptic gloves that uses vibrotactile actuators and open-source electronics. A Leap Motion sensor [28] tracks hand and finger motions, while a head-mounted 3D display provides intuitive visual stereoscopic feedback. Using a headset with a built-in microphone provides an extra bidirectional audio channel. The Unity cross-platform 3D environment [29] is chosen to properly integrate these aspects. Successively, a new prototyping iteration was implemented aiming at improving the robustness of the proposed framework [24]. To demonstrate the potential of the redesigned framework, two human subject studies in virtual reality (VR) were considered. Results proved that the proposed haptic-enabled framework provides good rendering performance and a realistic illusion of presence. These studies demonstrate that it is possible to fabricate immersive tools that are economical, customisable, and fast to fabricate.

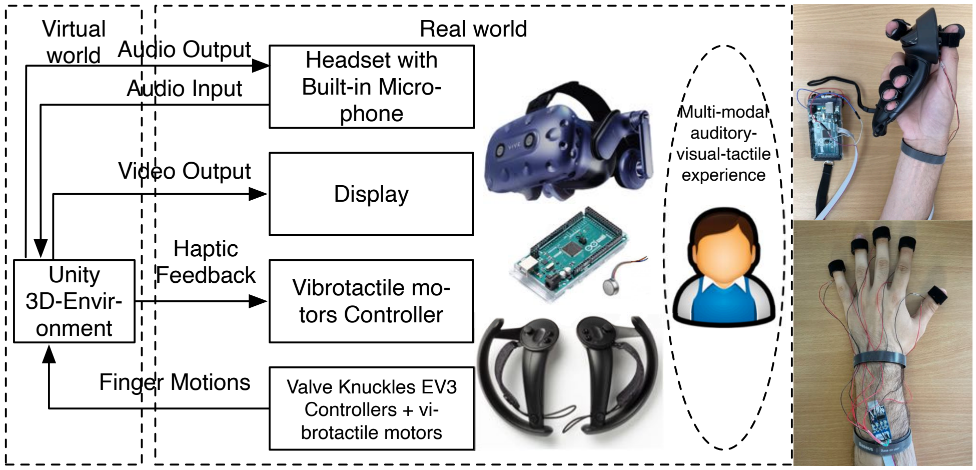
In line with these same designing guidelines, this paper introduces an innovative haptic-enabled architecture for hands-on e-Learning. This is accomplished by integrating VR tools with a novel wearable haptic device created by adding vibrating actuators to a COTS controller. To achieve this, the Unity gaming engine [29] and the Valve Knuckles EV3 [30] controllers are employed. A human subject study is conducted to show the possibilities of the proposed framework.

The paper is organised as it follows. A review of the related research work is given in Section 2. In Section 3, the proposed framework architecture is presented. The considered human subject study is described in Section 4. In Section 5, simulation results are outlined. Finally, conclusions and future works are discussed in Section 6.

2 Related Research Work

The majority of haptic devices that are currently available on the market cannot be considered fully wearable. Interfaces like those of the *sigma.x*, *omega.x* and *delta.x* series (Force Dimension) or the *Phantom Premium* (3D Systems, Inc.) are usually accurate, and able to provide a wide range of forces. In literature, they are called “grounded” interfaces, as their base is fixed to the ground [19]. The pursuit of more wearable haptic technologies lead researchers to the development and design of exoskeletons, a type of haptic interface which is grounded to the body [13]. Even if exoskeletons can be considered wearable haptic systems, they are often quite heavy and cumbersome, reducing their applicability and effectiveness. This is why, in recent years, research efforts in the field of haptics focused on the development of a new generation of wearable haptic interfaces. Haptic thimbles [14, 21], haptic rings [15, 18], and haptic armbands [2], have been successfully applied in different applications, ranging from teleoperation and VR or augmented reality (AR) to human guidance. The key feature enabling wearability of such devices is that the grounding of the system is coincident with the point of application of the stimulus. As a consequence, the haptic interface is only capable of providing cutaneous cues that indent and stretch the skin [7], and not kinaesthetic cues, i.e., stimuli that act on skeleton, muscles, and joints [10]. Wearable haptic interfaces, providing only cutaneous stimuli, do not exhibit any unstable behaviour due, for instance, to the presence of communication delay in the closed haptic loop [17]. As a consequence, the haptic loop with wearable tactile interfaces results to be intrinsically stable.

Regarding the application of haptics for e-Learning, a multimodal haptic simulator was presented in [8]. The haptic simulator helps student comprehension of complex ideas (e.g., physics topics) and has the potential to supplement or replace traditional laboratory training with an interactive interface that improves motivation, retention, and intellectual stimulation. A review and early pilot test of haptic tooling to support design practice, within a distance learning curriculum was recently presented in [5]. However, most of these works still adopt relatively expensive haptic devices that are yet not available to the vast majority of students. Hence, our research group recently presented a novel perspective for a sustainable integration of virtual and augmented reality (VR/AR) with haptic wearables into STEM education to achieve multi-sensory learning [22]. To the best of our knowledge, a low-cost and open framework for a fully-immersive haptic, audio and visual experience is still missing for e-Learning laboratory skills and student engagement.



(a) (b)

Fig. 1: The proposed framework: (a) the framework architecture, (b) the Valve Knuckles EV3 controllers augmented with vibrotactile motors.

3 Framework Architecture

The proposed framework architecture, encompassing software, hardware, and multi-modal rendering strategies, is described in this section.

3.1 Software Architecture

The framework architecture is depicted in Figure 1-a. In the following, the key elements of the system are presented.

The primary components of the proposed framework are the COTS Valve Knuckles EV3 controllers. These controllers combine complex sensor inputs to track hand position, finger position, motion, and pressure to determine user intent. We have equipped these controllers with precise shaft-less vibrotactile motors embedded on the outer shell, as shown in Figure 1-b. Distinctive haptic feedback patterns may be communicated to the user via these motors, accurately simulating virtual finger collisions. The controller for the motors is implemented on an *Arduino Mega* board [1]. The *Arduino* is an open-source electronics prototyping platform that uses flexible, user-friendly hardware and software. A variety of libraries are provided by *Arduino* to make programming the microcontroller easier. As a result, software development and, by extension, hardware development are simplified, cutting down on the time it takes to prototype a system. The choice of adopting an *Arduino* board makes the motor controller simple to maintain and allows for the addition of new features in the future. The Valve Knuckles EV3 controllers, which are augmented with vibrotactile motors, represent a significant advance when compared to similar COTS devices since they

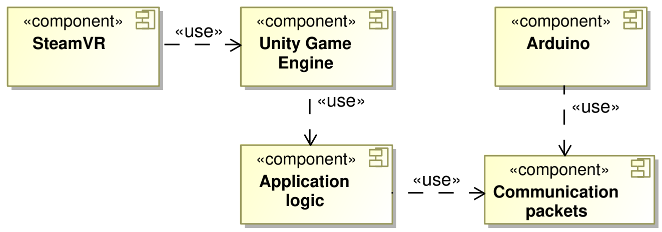


Fig. 2: The components diagram of the proposed system.

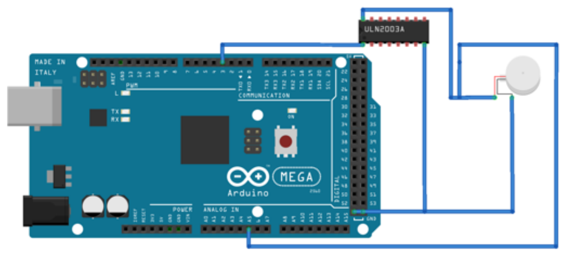


Fig. 3: The control circuit for one vibrotactile actuator.

are easy to obtain by just using simple additional components, and they are resilient and low-cost. The *SteamVR* application programming interface (API) is then used for the integration with the visualisation environment.

The *Unity* cross-platform 3D-environment [29] is chosen as middleware for the integration of all framework components. The HTC VIVE Pro VR headset is adopted to provide the user with realistic visual feedback (a common computer monitor can also be used to lower the cost) and with a bidirectional audio channel to enhance the user experience.

Based on the Unified Modeling Language (UML), a component diagram is shown in Figure 2.

3.2 Hardware Implementation

One of the embedded vibrotactile actuators and the corresponding control circuit is shown in Figure 3. The motors are driven by a ULN2003 stepper motor driver module. Three 1,5 V AA alkaline batteries are used to power the circuit for a total of 4,5 V.

3.3 Multi-Modal Rendering Strategies

For the collision detection, finger ray casting is adopted [11], as shown in Figure 4. For the i-th finger, a ray is casted, from the finger tip, in the forward direction, against all object colliders in the scene when within a length t, which is the

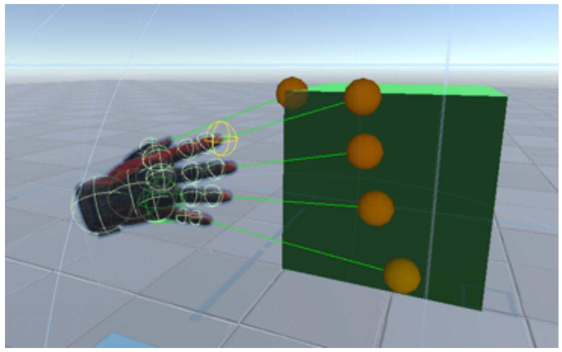


Fig. 4: The implementation of finger ray casting for collision detection.

distance tolerance. This makes it possible to calculate d_i, which is the distance value of the representative i-th contact.

Based on [24], the tactile rendering system employs a force calculation paradigm in which the amount of force exhibited is related to the penetration depth or separation distance [12]. The i-th force F_i is given by:

$$F_i = k(t - d_i) - k_v v_i, \tag{1}$$

where v_i is the i-th approaching velocity. While, k and k_v are stiffness and damping constants, respectively. The force is then rendered by using a Pulse Width Modulation (PWM) signal, where the duty cycle of the i-th vibration actuator, D_i, is proportional to the force to be rendered normalised between the specific actuator range, as shown by the following equation:

$$D_i = \frac{\alpha F_i - F_{min}}{F_{max} - F_{min}}, \tag{2}$$

where α is a scaling factor. While, F_{min} and F_{max} are the minimum and maximum renderisable forces, respectively.

Furthermore, auditory rendering is obtained by generating a sound feedback with a pitch that is proportional to the force to be rendered normalised between the specific frequency range. The i-th pitch frequency, f_i, is calculated according to the following equation:

$$f_i = f_{min} \frac{\beta(F_i - F_{min})(f_{max} - f_{min})}{F_{max} - F_{min}}, \tag{3}$$

where β is a scaling factor. While, f_{min} and f_{max} are the minimum and maximum renderisable frequencies, respectively.

Similarly, visual rendering is achieved for the collision points by generating a colour feedback with a wavelength that is proportional to the force to be rendered normalised between the specific wavelength range (visible spectrum). The i-th wavelength, λ_i, is calculated according to the following equation:

$$\lambda_i = f_{min} \frac{\gamma(F_i - F_{min})(\lambda_{max} - \lambda_{min})}{F_{max} - F_{min}}, \tag{4}$$

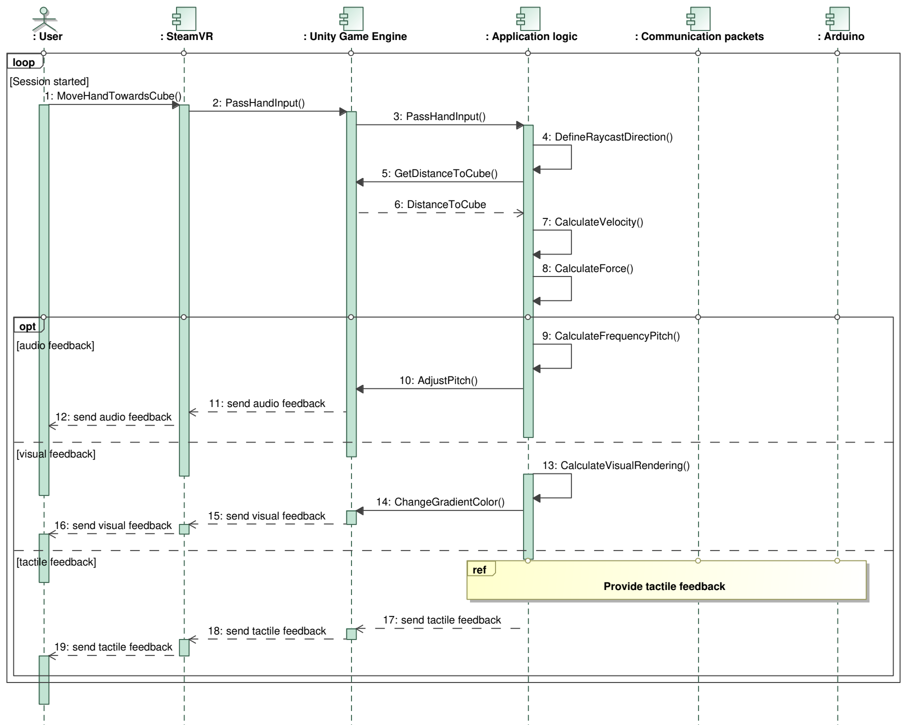


Fig. 5: A sequence diagram depicting the interaction with a virtual object.

where γ is a scaling factor. While, λ_{min} and λ_{max} are the minimum and maximum renderisable wavelengths, respectively.

The multi-modal rendering is achieved by simultaneously combining auditory, visual and tactile rendering together, as depicted in the sequence diagram shown in Figure 5. When a finger moves towards an interactive virtual object (i.e., within the distance tolerance), the SteamVR component detects this movement and sends the corresponding input signal towards the main application logic component. When this signal is received, the application logic component defines the direction in which the ray cast should be drawn. According to the interactive collision, the Unity Game Engine provides the distance between the finger tip and the colliding virtual object on the corresponding casted ray. After successfully determining the distance of collision, the application logic component estimates the velocity at which the finger is moved towards the colliding object. Consequently, the force is calculated and the corresponding tactile feedback is rendered. To render the audio feedback, the application logic calculates the required frequency level, then adjusts the pitch according to the calculation and renders the audio feedback through the virtual reality headset. Visual

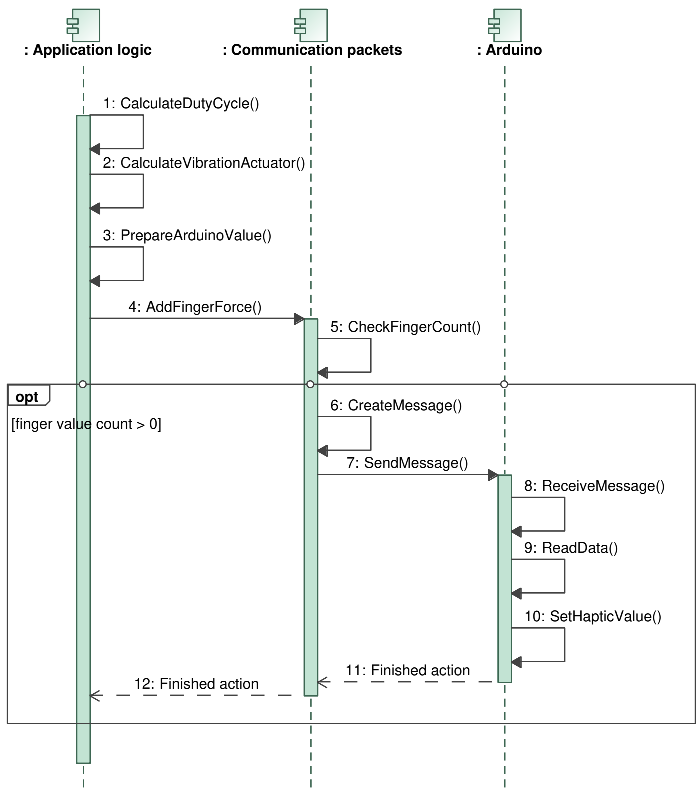


Fig. 6: A sequence diagram of the procedure for rendering of tactile feedback.

feedback is rendered in a similar manner - the system calculates the required wavelength, which is then displayed to the user.

As shown in the detailed sequence diagram of Figure 6, to render tactile feedback, the application logic component calculates the duty cycles to be sent to the motors. These values are prepared to be sent to the Arduino through communication packets component. When the values are sent through communication packets, the system checks how many fingers should receive the feedback. If there are no fingers in contact, the system does not send any signals to the Arduino. Otherwise, if there is at least one finger in contact, the communication packets component creates a message, which is then sent to the Arduino. The Arduino simply actuated the received values to the motors. Consequently, the tactile feedback is perceived by the user.

4 Human Subject Study

To demonstrate the potential of the proposed framework, a case study is presented. In particular, an educational approach to the recycling and disposal of domestic waste is considered. The aim is to increase both academic and public awareness for this process. Recycling includes a series of activities consisting of collecting any kind of recyclable materials that would otherwise be considered waste, sorting and processing them into raw materials. In the considered case study, we focus on the sorting procedure. As shown in Figure 7, a simulated scene is created including two main interactive stations: 1) a counter where unsorted waste items are laid up; 2) a sorting counter with allocated/marked collecting regions for paper, glass and plastic materials. The underlying idea is that the user would learn how to properly sort out home waste by participating into a multi-modal auditory-visual-tactile experience. A game-based learning and gamification approach is adopted to promote user engagement and motivation. The goal is to sort all waste materials in the shortest time possible. From a grasping perspective, waste objects composed of shape primitives like cuboids, cylinders and spheres are considered. This is relevant because it makes it possible to assess grasping procedures that could potentially be generalised to different types of objects [25, 27, 26].

A number of human subjects is selected for this study. In particular, 10 persons participate to this preliminary study. Each participant is first asked to familiarise with the simulation environment and successively is asked to perform the following test sequences: a) sorting materials by using only visual feedback; b) sorting materials by using auditory and visual feedback; c) sorting materials by using a combined auditory, visual and tactile feedback.

For each test, a timer is started when the user first touch any of the waste objects. The timer is stopped when all the waste objects are properly sorted. Moreover, a user survey is conducted immediately after the test session. In particular, the Igroup Presence Questionnaire (IPQ) [20] is considered. The IPQ test is a scale for measuring the sense of presence experienced in a virtual environment (VE). The current version of the IPQ has three sub-scales and one additional general item not belonging to a sub-scale. The three sub-scales, which can be regarded as independent factors, include: a) spatial presence - the sense of being physically present in the VE; b) involvement - measuring the attention devoted to the VE and the involvement experienced; c) experienced realism - measuring the subjective experience of realism in the VE. The additional general item assesses the “sense of being there”, and has high loadings on all three factors, with an especially strong loading on spatial presence.

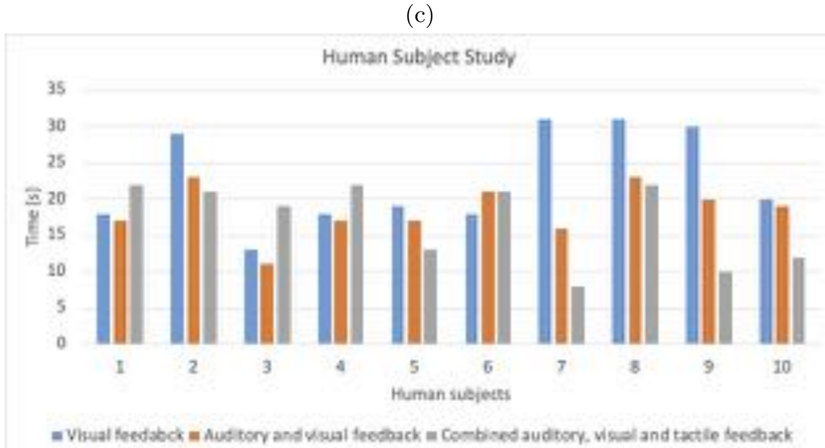
5 Simulations and Experimental Results

Figure 7 depicts the scene of one human subject sorting materials by using a combined auditory, visual and tactile feedback. A video depicting the entire experiment is available on-line at https://youtu.be/izcScavUGbo. The IPQ survey results for the multi-modal rendered experience are shown in Figure 8. These results are very promising regarding spatial presence and realism, while involvement is relatively well perceived on average.

(a)

(b)

(c)



(d)

Fig. 7: The results of the conducted human subject study: (a) the objects to be sorted, (b) the sorting baskets, (c) a human subject sorting objects by using the combined auditory, visual and tactile feedback, (d) the time distribution for the selected test sequences.

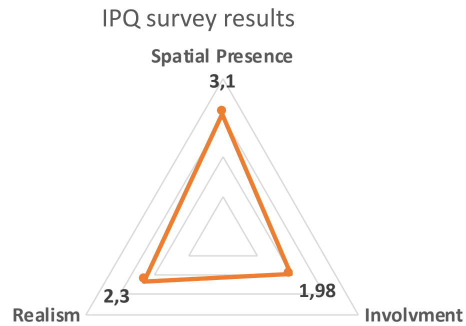


Fig. 8: The IPQ survey results for the multi-modal rendered experience.

6 Conclusions and Future Work

This study introduced an innovative haptic-enabled framework for hands-on e-Learning to offer safe, digital access to laboratories. A fully immersive tactile, auditory, and visual experience is achievable thanks to the proposed framework. This is accomplished by merging virtual reality (VR) tools with a novel wearable haptic device created by supplementing a low-cost commercial off-the-shelf (COTS) controller with vibrotactile actuators. The Unity gaming engine and the Valve Knuckles EV3 controllers are used for this purpose. A human subject research was performed to validate the developed framework. The considered haptic-enabled framework boosts student engagement and the perception of spatial presence, realism and involvement.

As future work, the proposed framework could be used to develop teaching modules and to test the concept with engineering students in an experimental setting [6]. This would make it possible to evaluate the applicability of the concept on a larger and practical scale.

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