Unlocking Potential: Gaze-Based Interfaces in Assistive Robotics for Users with Severe Speech and Motor Impairment

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***Abstract*— Individuals with Severe Speech and Motor Impairment (SSMI) struggle to interact with their surroundings due to physical and communicative limitations. To address these challenges, this paper presents a gaze-controlled robotic system that helps SSMI users perform stamp printing tasks. The system includes gaze-controlled interfaces and a robotic arm with a gripper, designed specifically for SSMI users to enhance accessibility and interaction. User studies with gaze-controlled interfaces such as video see-through (VST), video pass-through (VPT), and optical see-through (OST) displays demonstrated the system's effectiveness. Results showed that VST had the average stamping time of $28.45s(SD = 15.44s)$ and the average stamp count $7.36(SD = 3.83)$, outperforming VPT and OST.**

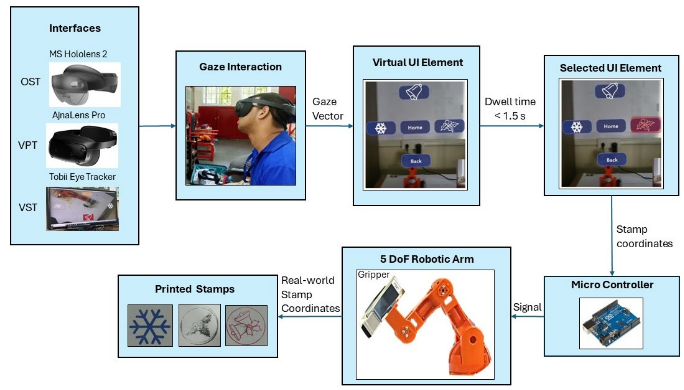

Fig. 1: Pipeline of the proposed system with gaze-controlled robotic arm and different interaction interfaces for stamping task

I. INTRODUCTION

All of us get fortunate in life in seeing children growing up. As a child starts to crawl, speak, walk, it brings joy to the parents and relatives. However, children with different range of abilities often follow a different development path than their able-bodied counterpart. In our previous work, we developed a Multimodal Joystick Controller that allows individuals with SSMI to control remote devices such as toy cars, drones, or robots using eye gaze [1]. Building on that, this work focuses on developing a gaze-controlled robotic arm enabling users to perform stamping task, supporting their developmental and rehabilitation process for those who are within the SSMI spectrum. Additionally, we designed a task-specific gripper to perform the stamp printing task.

With advances in human-robot interaction (HRI) and Augmeted Reality (AR) and Mixed Reality (MR) interfaces [2], head-mounted systems are often the first that come to mind. However, prolonged use of headsets can limit long-term adoption. To overcome this, video see-through (VST) interface offer 2D and 3D augmented reality features for practical applications and can be deployed without high-end rendering head-mounted systems. It integrates easily with eye gaze tracking and robotic systems. MR interfaces like video pass-through (VPT), and optical see-through (OST) have created new opportunities to improve accessibility for people with disabilities, particularly SSMI users, by blending virtual and real-world elements to enhance task performance and comfort.

A VST interface [3] utilizes cameras to capture the real-world environment, which is then displayed on a screen with virtual elements overlaid. In VPT interface [4], cameras capture the real environment and display it in real-time on a screen with virtual content seamlessly integrated. The distinction between VST and VPT lies in the immersive nature of the VPT experience, typically used in mixed-reality headsets. The OST interface [6] differs from the other two in that users view the real world directly through transparent lenses, with virtual objects (holograms) projected onto the lenses. However, there are key differences in the interaction methods used in VST, VPT and OST. In VST systems, users interact with on-screen elements by using their gaze. The eye tracker detects where the user is looking on the screen. It focuses on on-screen gaze selection through video feeds. VPT adds immersion by dynamically adjusting the virtual environment based on gaze and head movements. OST overlays virtual elements on the real world. The interaction here is also gaze -based where the eye trackers trackers where the user is looking. These differences affects user experience while performing tasks.

In this work, we conducted a study to analyze how both SSMI users interact with the gaze-controlled robotic arm using each of these interfaces. By assessing the average time for stamping and the number of stamps, we aim to determine which interface provides the most intuitive and effective interaction. For VST use used Tobii eye tracker [24] with video feed through a webcam on a 2D screen display. For VPT we use AjnaLens Pro [20] and for OST we use Microsoft Hololens 2 [19]. Through this evaluation, we aim to develop systems that not only improve task performance but also contribute to the rehabilitation and engagement of individuals with SSMI by providing accessible and comfortable human-

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robot interaction. Eye gaze controlled robotic manipulator pipeline is described in figure 1. The key contributions of the work are:

- Development of the gaze-controlled robotic manipulator equipped with a task-specific gripper, specially designed for individuals with SSMI.
- A comparative analysis of VST, VPT, and OST interfaces for robotic arm.
- Comprehensive user studies were conducted to examine the impact of these user interfaces through the stamping task.

II. Related Work

A major portion of SSMI population suffers from severe disabilities rendering them unable to talk, walk, and interact naturally with their environments independently [8]. Prosthetics and powered wheelchairs are common assistive technologies, which are not far away from robotic manipulator and mobile robots [10], [11]. Advance sensors and intelligent algorithms enable robotic arms to be used for independently feeding persons with disabilities by carefully monitoring humans, identifying food items on the table [12], planning their trajectory, and controlling [18] the orientation of the end effector [5], [13]. Robot exoskeletons help persons with limited mobility to walk and move around by inducing calculated electrical impulses in the muscles, amplifying the forces generated, and maintaining the upright posture for walking momentum [14]. Robots equipped with cameras and ultrasonic sensors help persons with vision impairments to safely navigate through everyday environments [15]. Repositioning and transferring robots help caregivers in assisting, and lifting elderly persons from wheelchairs for routine activities [16].

With advancement of head mounted displays (HMD), XR technology is increasingly being used for assistive applications. Recently, XR interfaces are widely being used with robotics for enhanced human-robot interaction. An XR system [17] with OST display was used to provide real-time 3D endoscopic visualization as a remote monitoring system for robotic surgery. *Rodrigo et al.* [9] designed an AR HMD user interface for controlling legged manipulators, offering enhanced usability, cognitive offloading, and immersion compared to traditional control methods. Other recent works in assistive robotics with XR interface includes [25], [26].

In our prior work, we introduced a VST interface for pick-and-place tasks [21] and developed a value iteration-based algorithm to ensure a safe distance from the robotic manipulator for SSMI users [22]. Building on this, we applied the safe distance algorithm to block printing tasks for SSMI users [23]. In this study, we designed a gaze-controlled robotic arm with a specialized gripper for stamp printing tasks. We evaluated the accessibility of three different interfaces(VST, VPT, and OST) for SSMI users by comparing average stamping time and the number of stamps achieved with each interface.

III. Proposed Approach

A gaze-controlled 5 degree of freedom robotic system able to manipulate a payload of 330 grams, was developed in enhancing the recreating activities of the user with SSMI. Besides that, eye-gaze controlled human-robot interfaces using VST, VPT, and OST technology were also developed for the individuals with SSMI. The development of the robotic arm with gripper and the gaze-controlled interface is described below:

A. Development of the robot

The development of this robot followed the embodiment design principles outlined in ”Engineering Design: A Systematic Approach” by Pahl and Beitz [7]. These principles ensured a structured approach to achieving the robot's functionality.

1) Robot design: The key parameters considered during the design of the robotic arm were (1) payload capacity and (2) accuracy. A 3D CAD model had been developed and 3D printed, with structural analysis conducted to ensure mechanical stability. The robot's degrees of freedom (DoF) provided the necessary range for performing the stamping task. The system featured a modular design with a specially designed gripper, as shown in Fig. 2a, allowing for easy maintenance and stamp replacement without disrupting the overall functionality of the system.

Forward kinematics was performed to determine the position and orientation of the gripper. Denavit-Hartenberg (DH) parameters were used to perform the forward kinematics. Let $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$ be the joint angles, and L_1, L_2, L_3, L_4, L_5 be the link lengths. For each joint i, the transformation matrix ${}^{i-1}T_i$, which described the rotation and translation from joint $i-1$ to joint i is given by:

$$ {}^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_i \\ \sin\theta_i\cos\alpha_i & \cos\theta_i\cos\alpha_i & -\sin\alpha_i & -\sin\alpha_i d_i \\ \sin\theta_i\sin\alpha_i & \cos\theta_i\sin\alpha_i & \cos\alpha_i & \cos\alpha_i d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The overall transformation matrix is given by:

$$ {}^0T_5 = {}^0T_1 \cdot {}^1T_2 \cdot {}^2T_3 \cdot {}^3T_4 \cdot {}^4T_5 $$

The gripper's position and orientation were determined by ${}^0T_5$.

2) Robot payload: The end-effector gripper, including the module and stamps, weighed $330grams$. To ensure the required payload, the system was designed to minimize strain on its mechanical components. The torque T_i needed to move the arm is given by:

$$ T_i = L_i \times A_i + \frac{1}{2} L_i \times W_i $$

$$ \Sigma T_N = T_N(\text{"holding"}) + T_N(\text{"motion"}) = I \cdot \alpha \quad (1) $$

where L_i is the length of the joint to the point where the load is applied, A_i is the acceleration of the mass W_i at the end of the arm or the component being moved. The required torque ranges from $1kg.cm$ to $3kg.cm$. Actuators with a safety factor of 3 were chosen to ensure reliability.

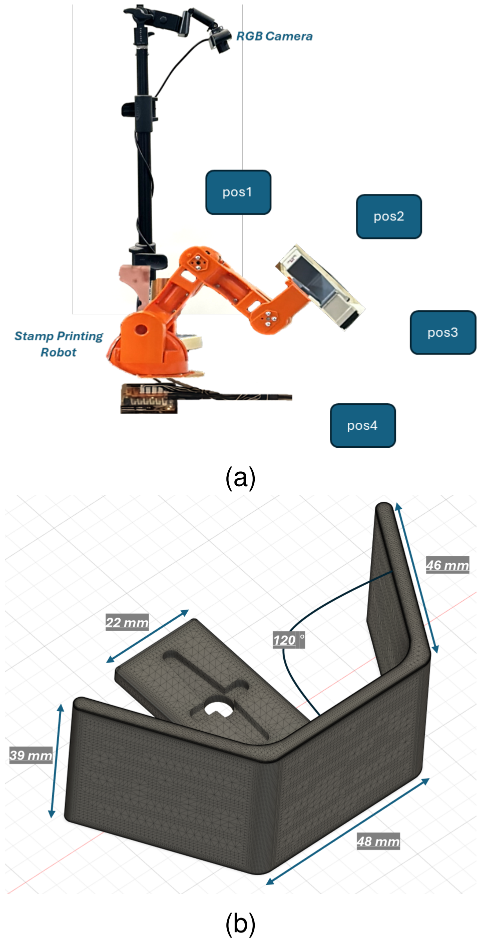

Fig. 2: (a) Developed stamp printing robot with gripper (b) 3D model of the stamp printing gripper

3) *Stamping gripper design:* The gripper was designed as illustrated in Fig. 2b accounting for motor skills of SSMI users, ensuring gentle and precise handling of the stamps. It could hold stamps and accurately position them on the desired surface. The applied torque (T) (Equation 1) on the gripper was calculated considering the safety factor in relation to the maximum allowable torque: The gripper holds three stamps in different directions, allowing for multi-directional stamping in a single operation. The design included angled surfaces and precise slots to securely hold each stamp while ensuring enough clearance for each stamp to be operated independently. Gripper development considered the forces needed to press each stamp and the alignment to ensure accurate printing. A stress-strain simulation on the 3D model of the gripper was performed to ensure it could handle the required stress. The gripper was prototyped using an FDM (Fused Deposition Modelling) 3D printer, and its functionality was tested in the lab.

B. *Gaze controlled user interface*

The gaze control system employs eye-tracking to interpret the user's gaze and translate it into commands for the robot. This feature allows SSMI users to operate the robot using

Algorithm 1 Robotic Stamping Task

Input: Interfaces, user, gazeInteraction(), hover(), dwellTime, UIpixel(), stampToReal(), ▷ Input parameters
for interface in Interfaces **do**
  gazeVector ← gazeInteraction(user) ▷ gaze vector estimation
  UIelement ← hover(gazeVector, dwellTime) ▷ UI element selection
  stampCoord ← UIpixel(UIelement) ▷ Stamp coordinate calculation
  realStampCoord ← stampToReal(stampCoord) ▷ Real world stamp coordinate
  return realStampCoord ▷ Return the result
end for

gaze. The gaze-controlled user interface include:

1) *Video see-through (VST) user interface:* A VST interface can be deployed without a head-mounted rendering system and can be integrated with an eye-gaze tracker and robotic manipulator. The proposed user interface is shown in Fig. 3d.

A user interface was rendered on the AR VST display enabling users to operate the display by dwelling their eye gaze on screen elements as illustrated in Fig. 3a. All virtual screen elements adapted their contrast based on ambient light conditions and the display matches the dimension of the physical world through an offset correction. As the user selects a screen element, a command was sent to the robotic arm to undertake an action fulfilling the users' intention.

2) *Video pass-through (VPT) user interface:* A mixed-reality VPT interface was developed for the AjnaLens Pro HMD, a device with a 4560 x 2280 pixel resolution, 90 Hz refresh rate, and a field of view between 95 and 105 degrees. This device provided an immersive and realistic experience. The proposed VPT interface was designed and deployed, ensuring smooth gaze interaction as shown in Fig. 3b. A key feature of the AjnaLens Pro was its lightweight design (400 grams) made it more comfortable than other HMDs. User performing the stamping task through AjnaLens is shown in Fig. 3b.

The deployment process involved integrating the UI with the AjnaLens Pro's software development kit (SDK). Once the scene was set up, the project settings for AjnaLens Pro compatibility were configured. Testing was conducted to ensure that the user interface provided a seamless and immersive experience.

3) *Optical see-through (OST) user interface:* A mixed-reality OST interface for the Microsoft HoloLens 2 HMD was designed with Mixed Reality Toolkit (MRTK). The device has a resolution of 1440x936 per eye and a 60 Hz refresh rate.

User interface was designed as shown in Fig. 3f. MRTK components were fully integrated into the project. The scene was set up with essential MRTK features including spatial awareness, and gaze input. The project was built through the Universal Windows Platform (UWP) with the Unity

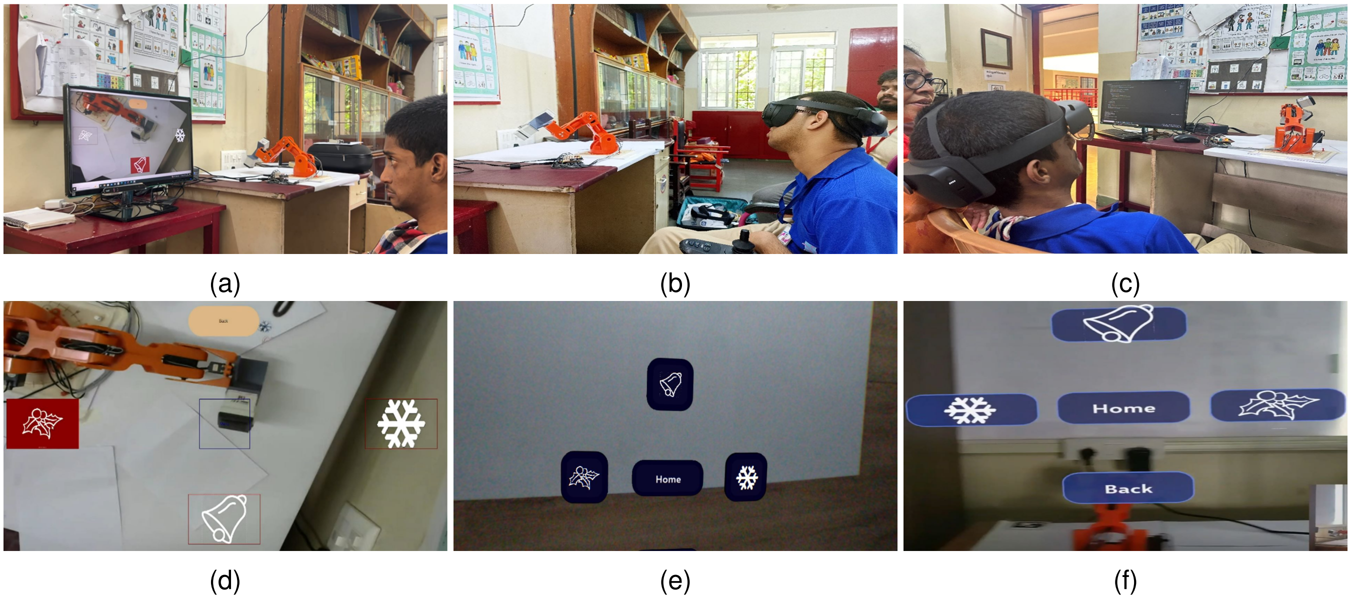

Fig. 3: (a) SSMI user using Tobii eye tracking to operate the stamp printing robot (b) SSMI user utilizing ajnalens headset (VPT) to operate the stamp printing robot (c) SSMI user using Hololens 2 headset (OST) to operate the stamp printing robot (d) AR video see through user interface (e) Mixed reality user interface integration with AjnaLens (f) Mixed reality user interface in HoloLens 2

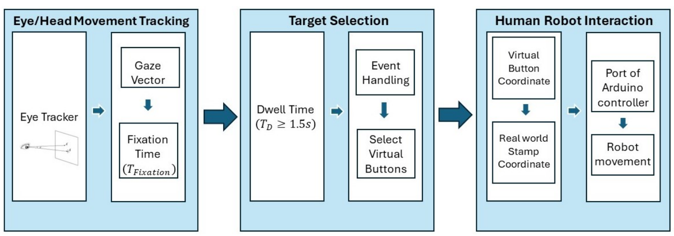

Fig. 4: Framework of target selection through eye gaze. A constant dwell time of 1.5 seconds was selected for target selection across all interfaces

project settings configured specifically for the device. The application was deployed and tested through user interaction as illustrated in Fig. 3c.

C. Target selection through gaze

The gaze vector was obtained through eye gaze using the eye tracker. Fixation counts (n) which is the total number of times gaze vector focuses on a specific region of interest (ROI) was obtained for the gaze vector. This helps to estimate the total fixation time which is the difference between start and end time of a fixation. This was used to calculate the dwell time T_D which refers to the total time a user spends gazing at a particular ROI. the dwell time is given by:

$$\text{Dwell Time}(T_D) = \sum_{i=1}^{n} T_{\text{fixation}_i} \tag{2}$$

For the stamping task, the interfaces with virtual buttons were the ROIs. The uniformity across all the interfaces, a common dwell time was selected. The target selection pipeline is shown in Fig. 4. In the VST system, a Tobii screen-based eye tracker utilized infrared light and cameras to detect reflections from the eyes, allowing users to select on-screen buttons by fixating on them. If the user's gaze remained fixed on a button for a specific dwell time, the system registered it as a selection. Similarly, the VPT system used AjnaLens HMD's integrated gaze interaction technology to estimate the gaze vector. By continuously monitoring head movements, it dynamically adjusted the virtual environment to align with the user's gaze. When the hand-held controllers were unlinked, users could select by focusing their gaze on a button. In the OST system, HoloLens HMD's eye-tracking technology allowed users to select virtual buttons on a holographic screen by detecting gaze fixations. Across all three interfaces, if the user's gaze stayed on the button for a dwell time $T_D \geq 1.5$ seconds, the system confirmed the selection, enabling interaction with virtual or holographic buttons through eye gaze.

Similar to eye tracking, eye calibration varies across VST, VPT and OST. VST using Tobii eye tracker uses 3-point calibration whereas OST using HoloLens uses 6-point calibration. In point calibration, the user looked at a set of virtual targets equal to the number of points for calibration. These targets appeared one by one on the screen, and the user fixated on each as it moved to different positions. A successful calibration accurately maps user's gaze to the screen, ensuring precise gaze tracking. VPT using AjnaLens does not require calibration as it records gaze vector through head movement.

The summary of the proposed approach is given in Algorithm 1.

IV. User Studies

Following two user studies were undertaken:

1) Pilot study: This involved a VST interface to investigate a 4 DoF robotic arm for stamping task.
2) Confirmatory study: In addition to VST from the pilot study, this involves VST, VPT and OST interfaces for the Stamping task using the propose 5 DOF robotic arm (Section III-A.1) with a gripper (Section III-A.3). The study was undertaken five months following the pilot study to quantitatively compare user performance for accessibility across interfaces.

A. Pilot study

In the pilot study, the VST was tested with 7 SSMI users, and all of them were able to complete the task. The users executed the task by using gaze to interact with the UI and, consequently, the robot. Their gaze was continuously tracked by the Tobii eye tracker placed below the screen. If the dwell time on a particular button exceeded 1.5 s, the button was selected. A color change in the selected button provided visual feedback to the user. A real-time video stream of the robotic arm was displayed on the screen via a webcam. The robotic arm moved towards the selected button on the screen and made a print. The total task completion time and the number of stamps were recorded for each user.

TABLE I: Pilot study: Engagement and average stamping time using VST

User	User Condition	Eng. Time(s)	Avg. stamping time (s)	UI Experience
P1	Muscular Dystrophy	90	90	Overwhelmed
P2	Cerebral Palsy	456	228	Comfortable
P3	Cerebral Palsy	499	166.33	Comfortable
P4	Cerebral Palsy	162	162	Overwhelmed
P5	Cerebral Palsy	345	69	Comfortable
P6	Muscular Dystrophy	252	84	Very comfortable
P7	Cerebral Palsy	217	54.25	Very comfortable

B. Confirmatory study

A confirmatory user study was conducted to assess how SSMI users perceived the usefulness of the robot stamp printing task across three different interfaces. The robotic stamping system had been improved and optimized to meet the requirements of SSMI users. User studies of the system demonstrated its effectiveness and potential for increased user engagement.

1) Participants: 11 SSMI participants volunteered for the study. Before the study began, consent was obtained from both the participants and their caregivers. The study was approved by Vidya Sagar, a disability services and support organization in Chennai, Tamil Nadu, as well as the Institutional Human Ethics Committee of the Indian Institute of Science, Bengaluru (IHEC No: 01/3.12.2021). All ethical principles were followed, and informed written consent was obtained.

2) Materials: The study involved Tobii Eye Tracker PC Mini Eye, Ajnalens Pro, and Microsoft HoloLens 2 for gaze interaction. The VST experimental setup included a Windows 11 desktop with a 36-inch sRGB monitor at 1920 × 1080 resolution for rendering. A C270 HD webcam with 720p resolution was mounted on a tripod to capture the stamping area. An in-house-built robot, an Arduino-based five-degree-of-freedom robotic arm with a motor driver, and a 3D-printed gripper end-effector were used. Visual Studio was employed to design the VST interface, while Unity 3D was used to create the VPT and OST interfaces.

3) Design: The users' task involved a stamp printing task where the SSMI user looked at the robot, and using VST, VPT, and OST users executed the task by using gaze to interact with the robot as shown in Fig. 3. Users' gaze were continuously recorded by the system. If the dwell time at a particular button was greater than 1.5 seconds, the button was selected. The selected button turned red providing visual feedback to the user.

4) Procedure: A randomized t-table method was used to allot all participants their first interface method prior to starting the study, which was available only to one investigator who was not involved in participant recruitment, to avoid selection bias. After each trial, the total task completion time and number of stamps were recorded for each participant.

V. Results

Engagement time refers to the total duration a user spends in performing the task. The engagement time for the participants during the pilot study using VST interface is shown in Table I. The average engagement time for the task was $288.714s(SD = 151.33s)$. Each user printed multiple stamps. The average number of stamps for the VST interface was 2.143. The average stamping time for each participant is given by:

$$Average\ stamping\ time = \frac{Engagement\ time}{Total\ number\ of\ stamps} \quad (3)$$

The average stamping time for the participants during the pilot study is given in Table I. The average stamping time for the pilot study was $121.94s(SD = 62.16s)$. The high stamping time was attributed to the complex robotic system with a naive gripper design for stamping. From Table I, it can be noted that 3 users found the experimental setup using VST and the gaze-controlled robotic arm to be *comfortable*. Two participants found the setup to be *overwhelming* with one of them mentioning the UI to be extremely cluttered. Two participants found the task extremely comfortable, with one easily able to fixate eye gaze and the other printing the highest number of stamps. The high average stamping time and overwhelming user experience necessitates for the development of an efficient gaze-controlled robotic system especially for the SSMI users with an user-friendly UI for the stamping task.

As part of the confirmatory study, a gaze-controlled robotic arm with a task-specific gripper and an efficient UI for SSMI users was designed. The study evaluated three interfaces: VST, VPT and OST, each emplying different eye-tracking. The average stamping time and the number of stamps across different interafces are shown in Fig. 5. The average stamping time for VST was the lowest with $28.45s$, followed by OST and VPT with $37.97s$ and $40.31s$ respectively. The average number of stamps for VST, VPT and OST were 7.36, 6.64 and 6.27 respectively. The system demonstrated an average stamp count of at least 6.27. The system shows SSMI users were already familiar with VST system from the pilot study, resulting in faster stamping times and the highest number of stamps with VST compared to the other interfaces. The average number of stamps using VPT and OST were similar. The shorter stamping time for OST indicates that SSMI users completed the task more quickly with the HoloLens than with the AjnaLens.

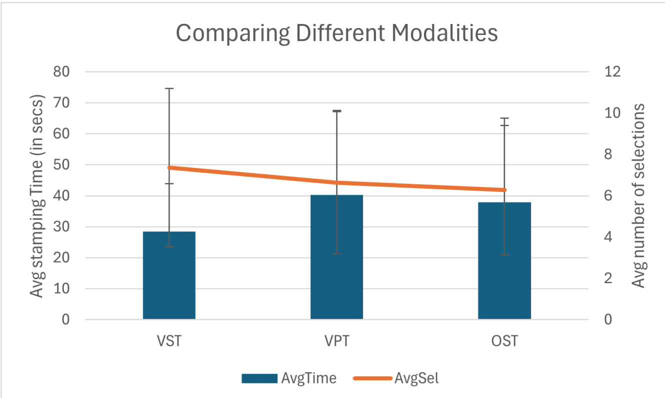

Fig. 5: Comparison of stamping time and number of stamps for different interaction interfaces. Primary Y-axis shows average stamping time, while secondary Y-axis shows average stamp count, and X-axis shows different interfaces

To analyze the significance of the different interfaces on number of stamps, one-way ANOVA and paired t-tests were conducted. We did not find a significant interaction effect of the interfaces on the number of stamps, $F(2, 30) = 0.280$, $p = 0.757$. Additionally, paired t-tests confirmed that different interfaces had no significant impact on the number of stamps. There were no significant differences between the VST and VPT interfaces in terms of the number of stamps ($t(10) = 0.484$, $p = 0.319$). Similarly, no significant differences were observed between the VST and OST interfaces ($t(10) = 0.907$, $p = 0.192$),and between the VPT and OST interfaces ($t(10) = 0.266$, $p = 0.397$).

To analyze the significance of the different interfaces on stamping time, one-way ANOVA and paired t-tests were conducted. We did not find a significant interaction effect of interfaces on stamping time $F(2, 30) = 0.759, p = 0.476$. No significant difference between VST and VPT interfaces on average stamping time ($t(10) = -1.394$, $p = 0.193$) was reported. No significant difference between VST and OST interfaces on average stamping time ($t(10) = -1.173$, $p = 0.268$) was reported. No significant difference between VST and OST interfaces on average stamping time ($t(10) = 0.234$, $p = 0.820$) was reported.

VI. Discussion

Results from the pilot study displayed various experiences of the gaze-controlled robotic arm with the VST interface. While the SSMI user was able to learn the stamping task with the long duration. The average stamping time in pilot study was 121.94 s. The confirmatory study brings improvement with an average stamping duration of 28 s. This reduction demonstrates that design improvements in the robotic arm and gripper made the stamping task easier for the SSMI users. The robotic arm from the pilot study was 4 Dof whereas a 5 of robotic arm was used for the confirmatory study. SSMI users faced difficulty using the two finger gripper for stamping during the pilot study. This increases the average stamping time. To overcome this, a gripper design with multiple slots for stamping was proposed. This gripper design results in lesser stamping time. The same reason could be attributed for increase in average number of stamps from 2.14 to 7.36 using the VST interface.

SSMI users have a lesser focus on day to day tasks compared to able-bodied users. VST interface being open to environmental distarctions, distracts SSMI more compared to VPT and OST interfaces which are closed and displays the UI in front of the user. However, despite higher distraction, VST significantly performed better by achieving highest number of stamps and lowest average stamping time compared to VPT and OST during the confirmatory study. This is due to the participants' prior exposure to VST interface during the pilot study, leading to familiarisation of the system. Lower latency (refresh rate) of VST compared to VPT and OST is also responsible for superior performance of VST compared to other interfaces.

Due to cameras displaying real and virtual components in VPT, the display in VPT flickers. This induces slight distraction for the SSMI users resulting in higher stamping time than OST which project holograms into the real world. Despite the AjnaLens being lighter, its eye gaze estimation is different from HoloLens. The AjnaLens with the VPT interface relies on head movement for selecting target buttons, while the HoloLens with the OST interface uses IR cameras for eye tracking. This distinction is critical for SSMI users who have unstable head movements, as it leads to poor target selection with VPT, resulting in longer stamping times compared to OST.

VII. Conclusion

In this work, we developed a gaze-controlled robotic arm with a task-specific gripper for SSMI users. A comparative analysis of VST, VPT, and OST interfaces was conducted for the stamping task. User studies revealed that the VST interface achieved the lowest average stamping time and the highest stamp count, enhancing system accessibility. This study offers an efficient and practical solution for SSMI children, enabling them to perform tasks like stamp printing independently and engagement in daily activities.

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