Augmented Reality Instructions for Shared Control of Hand-held Robotic Systems

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Abstract— **Handheld robotic systems have to rely on the human user to implement large scale movement of the system. Allowing the user to act without direction can limit the type of algorithms that can be effectively implemented. Here we introduce a feedback system using Augmented Reality (AR), that can request specific trajectories to be implemented by the user. This work includes two contributions. Firstly the accuracy of an untrained human user completing a trajectory with a hand-held robot is characterised. We found that designers should expect upto 63mm error in robot position and 0.18rad (10°) error in orientation when the user is given augmented reality guidance. Secondly we have demonstrated that providing augmented reality guidance can significantly improve the accuracy of speed regulation, position error and orientation error by 19.3%, 15.5% and 39.2% respectively. This is compared to a situation when the user has full knowledge of the trajectory expected of them, but no substantial visualisations to guide them.**

I. Introduction

Hand-held robotic systems offer a number of advantages over traditional stationary and mobile robots. Much of the bulk, complexity and cost of articulation and mobility can be absorbed by the human user. This shift of complex tasks away from the robot can allow for the design of the robot to be more effective at the elements of the task where the robot adds the most value. For example in the situation where the task is to apply a liquid coating to a large complex object. Rather than having a large gantry based robot, or a complex and expensive mobile robot, a human can be used to deploy a hand-held robot to the correct location, and the precise task of application and measurement can be performed by the robot.

Such a system may be able to fill a niche between highly precise robotic arm based spraying robots, typically used on production lines, and highly trained technicians knowledgeable enough to complete one off tasks effectively with manual spray equipment. A hand-held system would offer some of the precision of a robotic system and some of the flexibility of a manual spraying system.

However in order to have a hand-held system work effectively the robot and the user must have a shared understanding of the task at hand. Head mounted augmented reality is a promising technology for communicating information to a user whilst allowing them to work with as little hindrance as possible. This is because by default augmented reality systems allow the user to see the real world, allowing them to see potential hazards in the work environment, unlike a virtual reality system that must always take into account such hazards and make them available to the user in the visualisations shown to them. Additionally for tasks demanding dexterity and hand eye coordination, such as the spraying task we are considering, augmented reality allows those functions of the user to not be impaired. Allowing the designer to focus on improving the experience, rather than finding ways to avoid hindering it.

This work seeks to provide designers of augmented reality systems for hand-held robots an estimate of what degree of accuracy they can expect from the user, as well as providing some preliminary demonstration that augmented reality visualisations can improve the accuracy and quality of movements over unguided movements. This was achieved by conducting a preliminary study of 8 people conducting trajectories that were both guided and unguided.

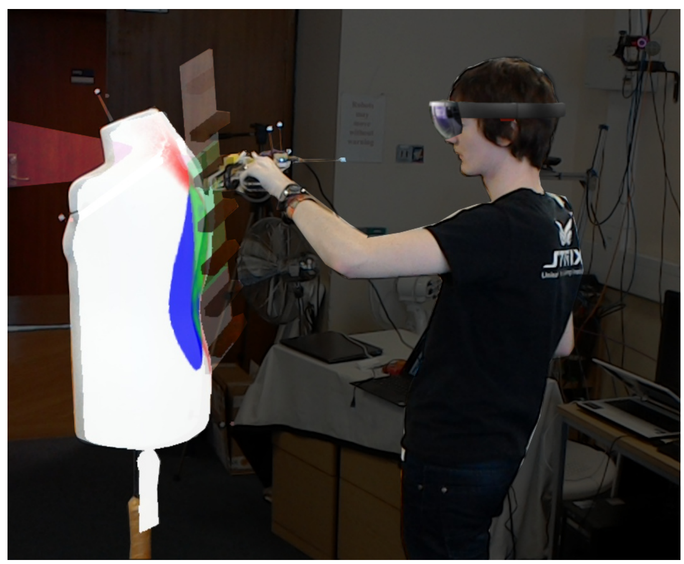

Fig. 1: This figure shows a 3rd person view of a user performing a trajectory using the detailed version of the visualisation. The hand-held robot and the mannequin are motion tracked by an infra-red camera system. This image was taken with the Microsoft Hololens, and would not normally be visible to a 3rd party. The Hololens has been added into the image and foreground elements highlighted.

A. Project Background

This work is a continuation of our work on assisted spraying technologies. Previously we have presented work[1] on how to automate a single axis hand-held robot using a receding horizon approach. That work put the decision making process in the hands of the human user, then the algorithm presented

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chose the best actuation strategy to apply the most liquid over a given time horizon. This approach can be effective, though it has a tendency to be greedy, making it difficult for the user to plan a global strategy. This was demonstrated in our recent work [2], where we performed a user study to measure the effectiveness of the approach. This study provided mixed results, some users found the assisted system cumbersome and found themselves fighting with the system. This work aims to provide the groundwork for shifting the the decision making capability from the user to the robot, with the expectation that this will cause less disagreement between the user and the robot. Further, agreeing on a plan of collaboration as presented in this work, could allow the development of algorithms for the hand-held spraying robot that take a global approach to planning, rather than the greedy, receding horizon approach.

B. Related Work

Gregg-Smith et al [3] presented a range of experiments comparing the efficacy of various user feedback methods in aiding the user to position a hand-held robot at a given location. They tested a monocular augmented reality headset, a virtual reality headset and a robot-mounted display, as well as a novel robot gesturing system. They concluded that all visual feedback methods performed similarly, both in regards to task completion and user task loading. However, this study also included a robot which could fully solve the task once in range of the target. This meant that the user was not required to perform any precise movements whilst using the robot. They did also present a non-robotic base line, where the user must align a wand with the target position to an accuracy of 5mm and 5° for 200ms, though this stationary goal is not informative for our problem of tracking set trajectories.

Research domains outside of hand-held robotics also offer some relevant insight. There is a wealth of work regarding sharing robot trajectory information with users and bystanders [4, 5]. Walker et al [5] for example explored a range of techniques to help a bystander understand the future movements of a flying robot. They found that their *Nav Points* method was particularly effective. Further it is our opinion that method was the most suited trajectory requests, if a user was part of the loop to implement the trajectory. This consisted of floating way-points that had the time till arrival displayed above, as well as the time till departure, for the case where robot intends to stay stationary at the way point for some time. Other methods presented offer less detailed information and would be less useful if the user was in control of implementing the path. However, in the use case the authors were discussing, the other methods also aided the user in perceiving the future trajectory of the flying robot.

Wu et al [6] demonstrated that augmented reality can be useful in guiding manipulation tasks. They used a monitor to display the assembly area with overlaid graphics giving contextual information on how to manipulate the various parts required to build a children's toy. This can be seen as similar to this work, though the information provided to the user is categorical and not time critical. For example, the command may be to *'Rotate the component!!'*, where there is no need to do this within a particular time frame, and no continuous amount of rotation is indicated. Our work could be seen as an attempt to do similar instructions with continuous and time critical actions.

II. Experimental Setup

The experiment consists of 8 trajectories that the users were asked to complete with the hand-held robot, both with a detailed visualisation and with a basic one. The visualisations are shown in Figure 2. The aim of providing a basic visualisation is to get some understanding in which ways a detailed visualisation could detract from the quality of motion, though for the purposes of making comparisons the users need some confirmation of the path they are expected to follow. Hence the simple visualisation is a minimalistic description of the direction they should follow. On the other hand the detailed visualisation shows the user the plane they are supposed to sweep with the gantry of the hand-held robot, where they should press and release the trigger and the speed at which they should be travelling. For all of the experiments the plane that they should sweep is the same distance from the mannequin. The mannequin is both physically present and rendered in the augmented reality system to provide confirmation that the calibration is working as expected. The speed was also the same for all trails, set at 30cm/s. This consistency was designed such that the user can have a full understanding of what trajectory they are expected to complete, even when there is only the simple visualisation indicating direction of the path to undertake.

Each of the participants were asked to complete 8 trajectories, where they completed each twice, alternating between the detailed and simple visualisations. Half of the participants undertook each trajectory with the detailed visualisation first, the other half with the simple one. This interleaving of the two types of trial is to help ensure the user has a very good understanding of the parameters of the trajectories (speed, hight above the mannequin etc) even when they are not shown these in the visualisation.

The trajectory of the spraying robot is captured by an infrared camera based motion capture system. The mannequin is tracked also so that the experimental area can be moved conveniently, though the mannequin was not moved during the trial for each user.

To ensure the visualisations are located accurately, virtual markers were manually placed on each of the motion tracking cameras. The reported location of the virtual markers was compared to the calibrated location of the cameras provided by the motion tracking software in a manner described by Ho et al[7]. This method provides a least squares approximation of the transform between the augmented reality coordinates and the motion tracking coordinates. Each of the virtual markers used the spatial anchor system provided by the Microsoft Hololens. This ensured that they would track any changes in the coordinate system of the AR headset. Though not measured formally for this work, the accuracy of this calibration method is roughly 1-2cm.

(a) Detailed Visualisation (b) Simple Visualisation

Fig. 2: This figure shows both the detailed and simple visualisations used in the experiments. The detailed visualisation has bars which move along the graphic at the speed that the user is expected to emulate. The user should aim to sweep the gantry of the hand-held spraying robot across the green section of the visualisation, whilst maintaining orthogonality of the robot to the trajectory. The user is expected to do all of the same things with the simple visualisation. The simple visualisation is only to help the user remember the direction they are expected move the robot along. The blue area has no bearing on this work, though is defined in previous work [1, 2]

III. RESULTS

The participants in this study were all familiar with the hand-held system and augmented reality headset used in this experiment and consisted of 2 females and 6 males. There are two categories of result that are of interest: relative quality measures and absolute quality measures. Relative quality measures do not reference the set trajectory, and absolute ones do. This distinction is important because it would be unreasonable to expect users to match parameters of a trajectory without being shown them, as is the case with the simple visualisation. However we can still analyse whether the movement that they did matched the general criteria that was asked of them, namely, the path should be straight, at a constant speed and the robot should be orthogonal to the direction of travel at all times. These general criteria match the assumptions that our algorithm uses to find paths in our previous work [1]. All of the results here are summarised in Table I.

TABLE I: A summary of the metrics analysed, their standard deviations, and the p-value when considering the proposition "the error is lower in the case of the detailed visualisation".

Error Metric	Units	Detailed	SD	Simple	SD	p-value
Abs. Position	mm	63.7	28.8	72.0	30.8	0.122
Rel. Position	mm	6.42	308	6.43	3.72	0.992
Trajectory Speed	mm/s	73.2	38.3	88.8	39.2	0.0255
Instant Speed	mm/s	157	51.6	178	62.4	0.0418
Abs. Orientation	rad	0.183	0.111	0.238	0.156	0.0265
Rel. Orientation	rad	0.314	0.129	0.350	0.146	0.136

1) Position Accuracy: The position accuracy was measured by taking the measured position of the robot and measuring the perpendicular distance to the trajectory. This is calculation is shown in Equation 1, where D is the distance from the line, S is the position vector of the start of the line, E the end, and P is the point under consideration. The absolute value of the distance was taken and averaged over the trajectory to arrive at the mean error from the trajectory. Participants performed better with the detailed visualisation with an average error of 0.0636m compared to 0.0720m (p=0.12).

However if we look at the error from the best-fit strait line of the users trajectory, we see no difference between the visualisation types, both diverting from the best fit line by an average of 6.4mm. This shows that the visualisation is not helping to keep the users travelling on a straight trajectory, through it does help them stay in the vicinity of the target trajectory.

$$D = \frac{\left\| \vec{SE} \times \vec{PS} \right\|}{\left\| \vec{SE} \right\|} \tag{1}$$

A. Speed Regulation

For all trials the users were required to move the robot at 0.3m/s. There are two metrics that are informative here, error in average speed over trajectory and speed error during trajectory.

The average speed of the robot ($S_{\text{trajectory}}$) was significantly more accurate with the detailed visualisation, 0.073m/s error, compared to the simple visualisation, 0.089m/s error (p = 0.025). During the movement it was possible to see some variation in the speed as users were trying to match the moving bars in the visualisation. If we look at the average error during the trajectory (S_{instant}), the detailed visualisation performs better with 0.16m/s error compared to 0.18m/s (p = 0.042). The fact that the instantaneous speed error is significantly larger shows that the users are better at estimating the speed over the whole trajectory rather than keeping a correct speed at any given moment. The method of calculating the average speed error ($S_{\text{trajectory}}$) and instantaneous speed error (S_{instant}) are shown in Equation 2 and 3 respectively.

$$S_{\text{trajectory}} = \frac{1}{N}(\sum_{i=0}^{N} s_i) - s_{\text{target}} \tag{2}$$

$$S_{\text{instant}} = \frac{1}{N}\sum_{i=0}^{N} \|s_i - s_{\text{target}}\| \tag{3}$$

B. Orientation Accuracy

The users were asked to keep the robot orthogonal to the direction of movement at all times, and in both versions of the visualisation the direction required is shown. Therefore we can have two metrics to measure the performance of the users' alignment accuracy, the relative orientation of the robot in regards to its movement direction, and the alignment with the requested orientation. In both of these metrics the detailed visualisation outperforms the simple visualisation, 0.31rad vs 0.35rad (p = 0.13) for the relative alignment, and 0.18rad vs 0.23rad (p = 0.026) for the absolute alignment.

IV. CONCLUSION

It can be seen that the more detailed visualisation allowed the users to perform better in all of the metrics. Though this is not a particularly surprising result, the users had access to more information from the more detailed visualisation. However, demonstrating the performance of the chosen visualisation over that of a lesser visualisation was not the aim of this preliminary work. Here we have demonstrated a base line for user movements with the robot with effectively no guidance, and demonstrated that even a somewhat simple visualisation displaying key information helps the user rather than hindering them. It is hoped that a designer of a similar system can use the data provided here to allow them to design assistive algorithms that are using assumptions about the users ability to comply with the instructions given. For example, an active head on such a spraying robot should be able to account for roughly 63mm of deviation from the planned path and an orientation error of 0.18rad (10 degrees), when the user has detailed information provided via an AR headset. However this would increase to 72mm position error and orientation error of 0.238rad (13.6 degrees) error if provided with less convenient spacial cues.

Most of the remaining error in moving the robot through trajectories is likely difficulty perceiving depth and obstruction of the real world by the visualisations. Future work could attempt to provide visualised feedback to the user regarding their performance, helping to emphasis the mistakes that they are making. Further, assistive algorithms for hand-held robots can be improved with realistic knowledge of the capability of the human user to comply with trajectory requests.

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