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Intuitive Robot Tool Path Teaching Using Laser and Camera in Augmented Reality Environment

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***Abstract*— This paper presents a new intuitive method for robot tool path teaching in Augmented Reality (AR) environment. Conventional industrial robot teaching method is long known to be either tedious or require a highly accurate virtual representation of robot work cell. Our method targets to provide the user with a fast and easy way of programming an industrial robot for useful tasks in a safe environment. In our system, a human robot interaction (HRI) system has been designed by fusing information from a camera and a laser ranger finder. The video images provide visual information to the user to operate the system, whereas the laser range finder captures the Cartesian information of the user intended robot working paths and trajectories. Furthermore, an AR environment has been designed where the virtual tool is superimposed onto the live video. The user simply needs to point and click on the image of the workpiece to generate the tool path. User can also adjust virtual tool orientation and simulate the tool trajectory in the AR environment, thus simplifying the robot teaching task. The proposed system has been tested for robot laser welding application. It is intuitive as no prior knowledge of robotic control is required in order to use our system. Most importantly, the system is safe and the user does not need to be physically close to the robot during path teaching.**

***Keywords*—** Human-robot interaction, Intuitive robot teaching, Augmented Reality

I. INTRODUCTION

In the manufacturing shop floor of small and medium enterprise (SME), the workpieces that require operator's attention are normally in large batch variation yet low volume. Typical manufacturing processes in SME include part handling, assembly and welding. It is sometimes very difficult to have a fully automated robotic system that can handle all these high mix, low volume tasks. Even if a robotic system has been designed for these applications, a team of experienced robotic engineers is required to re-program the robots frequently to suit the short term need of running a batch of works. This scenario is undesirable as it is both uneconomical and inefficient. Hence, a fast and easy method of robot programming is sought by both research community and industry partners.

A. *Related Works*

In general, robot teaching and programming is classified into two types: online and offline robot teaching. For online robot teaching, the robotic arm is powered on during the teaching process. For offline robot teaching, the robot working path is defined without the physical involvement of the robotic arm. Our proposed method falls in the class of offline robot teaching.

Traditional online robot teaching methods which include lead-through and walk-through teaching are both cumbersome and time-consuming. In lead-through programming, a teach pendant is used as the HRI device. The end effector posture, i.e. position and orientation are recorded while the robot is manually jogged to all targeted positions. This process is unfavorable from ergonomic point of view as controlling an industrial robot with six degrees of freedom requires the user to constantly adapt to think in different coordinate systems (world/robot/user centric) [1]. Walk-through programming on the other hand involves operator to freely hold and guide the powered robot end effector along a desired path with brakes disengaged [2]. The joint angle information is recorded and then played back during real operation. This method poses substantial safety concerns to the operator and is undesirable for hazardous working environment. Moreover both lead-through and walk-through teaching involve trial-and-error which greatly affects the accuracy of the teach points. The robot programming becomes tedious when the shapes of the paths to be taught are complicated.

Off-line programming using Virtual Reality (VR) is another common approach for robot teaching [3, 4]. Robot tasks can be planned conveniently in the VR environment as if the human operator is physically within the modeled remote working environment. This method allows the tool path to be simulated for reachability and collision checking. However to achieve offline programming, a complete geometrical description of robot working area and workpiece CAD model must be known a priori. Furthermore CAD model carry no information on their actual deviation in real world. Numerous calibration and workpiece localization efforts are necessary for programming the robot to work in a loosely structured environment.

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Augmented Reality (AR) is an innovative research area derived from Virtual Reality (VR). It creates a composite view by overlaying virtual elements, mostly computer generated graphics, onto the real world images such that both can be perceived by the users at the same time. When applied to robot programming, AR offers a unique solution for the operator to envisage the robot trajectories in the real environment. Unlike offline programming, robot teaching using AR does not require workpiece CAD models which may not be available in real case; as well as workpiece localization in work cell. Operator is able to intuitively interact with spatial information by adjusting the virtual tool to an optimal posture in the AR environment. The idea of applying AR towards industrial robot teaching was first explored by robot manufacturer KUKA in the cooperative research project MORPHA [5]. Similar implementations have been carried out that make use of marker-cube to guide the virtual robot for virtual operations within the work place [6, 7]. However conventional AR using marker-based optical tracking method is highly sensitive to occlusion. The tracking would when just a small portion of the marker is blocked in the camera view. Besides that, such system often suffers from large error while determining the marker depth information, even if a stereo camera is used [7].

In this paper, a markerless AR-based robot tool path teaching system that takes advantage of laser-camera fusion is presented. Instead of using marker-based optical tracking method, our approach applies a pan-tilt assembly unit (PTU) mounted with a laser range finder which provides accurate depth information to find the global coordinate of the desired position on workpiece surface. Knowing the frame transformation between the laser and the camera, precise 2D position in camera image is obtained for registration of the virtual tool. User can subsequently interact with the virtual tool to adjust its orientation as well as offset distance from the working surface. These parameters are difficult to define accurately using lead-through and walk-through methods. Computer vision algorithms are also explored to further enhance the path teaching process. Our system is targeted to be deployed in teaching industrial robot for laser welding operation. The paper focuses only on the tool path creation. The inverse kinematics study on the reachability issues of the path is not in the scope of this paper.

II. SYSTEM SETUP

A. *Hardware Components*

The system hardware components consist of a single-point laser range finder mounted on a PTU, a AVT firewire camera, a desktop-PC, and a ABB IRB 140 industrial robot. The laser range finder provides accurate range information with micro meter precision. The AR environment is programmed using open source OpenGL and ARToolKit libraries. The system hardware setup is as shown in Fig. 1.

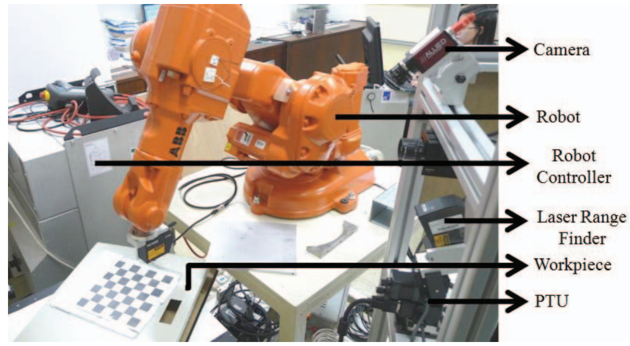

Figure 1: Hardware setup

B. *Geometrical Model*

In order to communicate specific real world position between different hardware components effectively, two important spatial relationships, namely robot to laser transformation, ${}^{R}\boldsymbol{T}_{L}$ and camera to laser transformation, ${}^{C}\boldsymbol{T}_{L}$ need to be calibrated in advance (refer to Fig. 2). ${}^{R}\boldsymbol{T}_{L}$ transforms the desired 3D coordinates of the points measured in laser frame into robot base frame such that robot knows where should it position the laser welding tool. Based on the same 3D coordinate value, ${}^{C}\boldsymbol{T}_{L}$ on the other hand tells the system the exact position in the image to render the virtual tool CAD model. Using a calibration marker board as the intermediate frame by finding ${}^{M}\boldsymbol{T}_{L}$ and ${}^{R}\boldsymbol{T}_{M}$, the two abovementioned spatial relationships can be resolved by homogenous transformation.

As mentioned previously, a laser range finder is used in our system to capture the 3D coordinate of a real world point in laser frame. The laser is mounted on a fixture at a vertical offset distance, H from the PTU which is free to pan and tilt at both Q_y and Q_x (refer to Fig. 3). The laser frame is defined to be aligned with PTU axis of rotation. For any point in the real world, P at a measured distance, D away from the laser range finder, its coordinate in laser frame can be computed as shown below:

$$ {}^{L}P = {}^{L}T_{curr}\, P = {}^{L}T_{curr} \begin{bmatrix} 0 \\ 0 \\ D \\ 1 \end{bmatrix} \tag{1} $$

where

$$ \begin{aligned} {}^{L}T_{curr} &= RotY(Q_y)\, RotX(Q_x)\ {}^{L}T_{home} \\ &= \begin{bmatrix} cQ_y & 0 & sQ_y & 0 \\ 0 & 1 & 0 & 0 \\ -sQ_y & 0 & cQ_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cQ_x & -sQ_x & 0 \\ 0 & sQ_x & cQ_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & H \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{2} $$

Hence from (1),

$$ {}^{L}P = {}^{L}\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} H\, sinQ_x\, sinQ_y + D\, cosQ_x sinQ_y \\ H\, cosQ_x - D\, sinQ_x \\ H\, sinQ_x\, cosQ_y + D\, cosQ_x cosQ_y \end{bmatrix} \tag{3} $$

To obtain ${}^{R}\boldsymbol{T}_{L}$, the laser range finder on PTU is first pointed to three predefined positions on the marker board. The robot with laser range finder mounted at its end effector is subsequently jogged to point to these same positions. The coordinates of these points in the two local frames are recorded to determine ${}^{M}\boldsymbol{T}_{L}$ and ${}^{R}\boldsymbol{T}_{M}$. ${}^{R}\boldsymbol{T}_{L}$ can be expressed as following:

$$ {}^{R}T_{L} = {}^{R}T_{M}\,{}^{M}T_{L} = {}^{R}T_{M}({}^{L}T_{M})^{-1} \tag{4} $$

Camera could not provide immediate 3D coordinates of the points on board unless it is calibrated for all its intrinsic and extrinsic parameters. After determining all camera intrinsic parameters such as focal length and distortion coefficients using standard calibration procedures [8], the extrinsic parameters or geometrical transformation of camera from marker board can be determined as. Finally the frame transformation of laser from camera is denoted as:

$$ {}^{C}T_{L} = {}^{C}T_{M}\,{}^{M}T_{L} = {}^{C}T_{M}({}^{L}T_{M})^{-1} \tag{5} $$

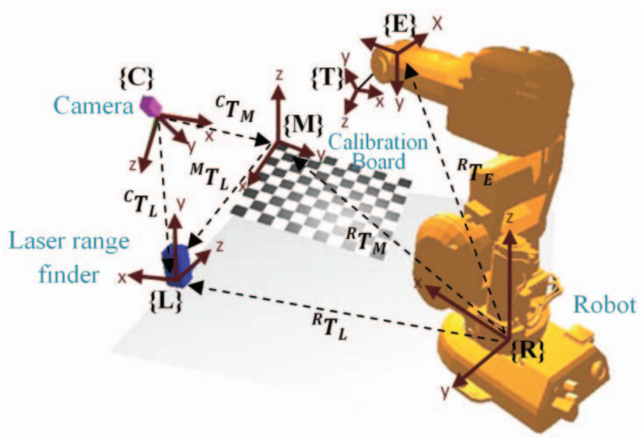

Figure 2: Frame transformation between system components

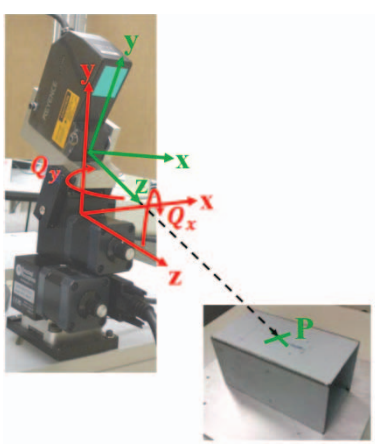

Figure 3: Laser 3D coordinate measurement unit

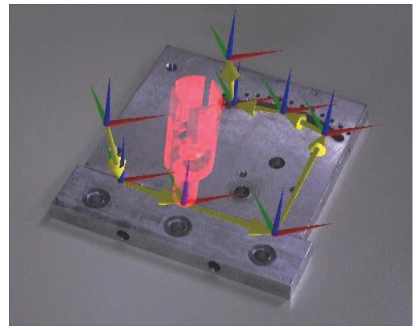

Figure 4: The AR (Augmented Reality) environment for robot tool path teaching. The virtual tool is overlaid on the real workpiece image to help users better visualizing the tool movement during robot teaching.

III. SYSTEM IMPLEMENTATION

Fig. 5 illustrates the architecture of the implemented system. The image of the workpiece is first captured by the camera and displayed in the AR environment. User can define a target position by simple point and click on the image. The PTU will bring the laser to point at the corresponding position on the workpiece to capture the Cartesian coordinate of the selected point. The laser spot is constantly being tracked by the system and will be seemed approaching and eventually coincide with the target pixel highlighted by a cross in the image. Upon acquiring the point 3D coordinate, a virtual frame axis and a virtual tool will be superimposed at that particular position which user can proceed to teach the subsequent target points (refer to Fig. 4). Two points are sufficient to form a straight line path on the workpiece for the robot to trace along. For circular, elliptical or arcs with random curvatures, the path is split into many segments which serve as multiple via points for the robot to move linearly across. The number of via points is based on user's decision. It will affect how closely could the robot follow these arcs. For laser welding, i.e. our targeted application, most paths are formed of straight lines joints.

After obtaining the point position of the path, user can further interact with the virtual tool in AR environment to change its orientation. The desired path with orientation defined will then be communicated to a robot program which will command the robot to execute the taught path.

A. *Laser Spot Tracking*

In order to correctly associate the image pixel with its corresponding position in real world, it is necessary for the system to detect and track the red laser spot projected by the laser range finder in the image at all times. The laser spot is recognized through color segmentation. The segmentation is performed in HSV color space representation in order to reduce the influence of environmental illumination to the detection result. A weighted sum of segmented pixels is taken as the centroid of the laser spot.

However problems arise in the tracking as the laser spot is constantly moving in the image during the process of path creation. Besides that, color segmentation result may be

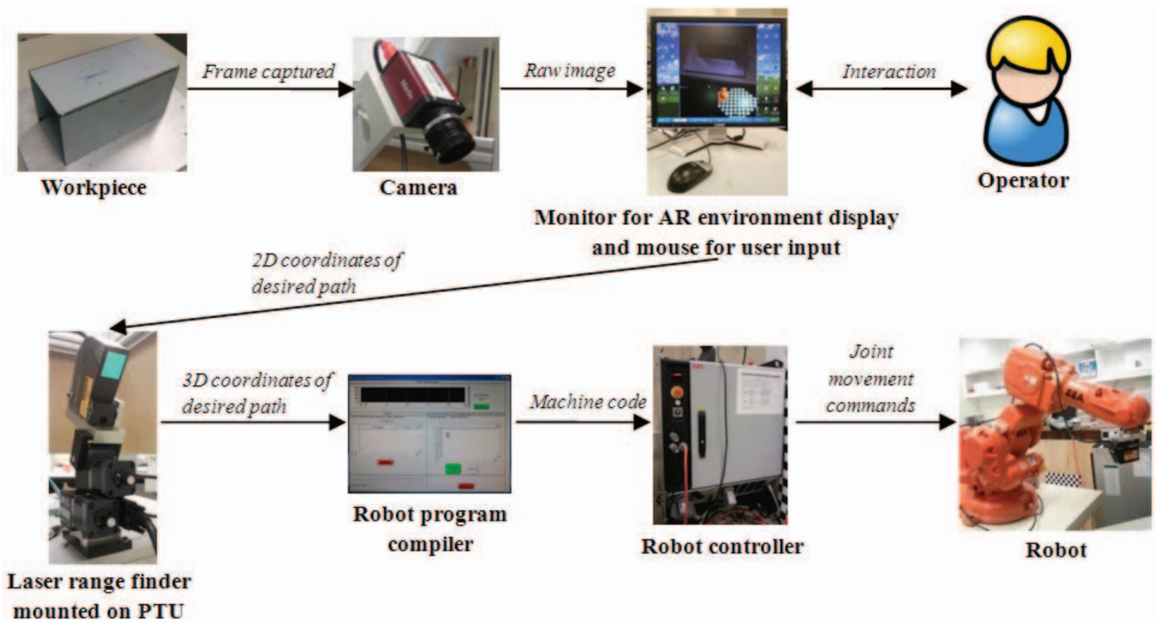

Figure 5: System Architecture

erroneous as there are noises due to chromatic aberrations [9] and other false positives in the scene. Furthermore when the laser spot is translating in the image due to the movement of PTU, its travel path may be discontinuous when there is an abrupt change in the ranges of surfaces that the laser is shone across. Laser spot may be reflected and split into several blobs when it is projected onto a shiny surface. Sometimes the laser spot may disappear for short instances if it lands in the blind spots such as holes or gaps on the workpiece. This resembles the conventional occlusion problem in the context of object visual tracking.

To overcome the abovementioned challenges, an efficient laser spot localization method using Kalman Filter as discussed in [10] and [11] is applied. Color segmentation is performed in specific region centered at the predicted position of the laser spot only, instead of searching for the spot in the entire image plane. Kalman Filtering is an optimal recursive predictor-corrector type estimator. It provides the best estimate for the laser spot current position through modeling the motion of the laser spot together with the system and measurement noises. The tracking starts with an initialization which the laser spot is searched in whole image to determine its initial position. This is followed by a prediction of laser spot current position based on the knowledge of its movement. The search window is then defined around the predicted location for detecting actual laser spot position. However this measurement value may not be perfectly correct due to possible noises in segmentation and presence of false positive. The measurement value is used to refine the predicted position, X_k which its level of influence is based on Kalman gain or Update gain that is calculated recursively from both system and measurement models. This gain can be seen as the degree of inclination of Kalman Filter on whether it should trust more on motion model or measurement information.

Laser spot tracking using Kalman Filter reduces computation overhead significantly and results in a higher detection frame rate. Kalman Filter also offers advantage of tolerating small occlusions to the laser spot tracking algorithm. Whenever there are multiple false positives found within the search window, the red blob that is closest to the predicted position will be selected as the laser spot.

B. Path Generation Using Line and Curve Detection

The five basic types of weld joints encountered in conventional laser welding process are the butt joint, lap joint, corner joint, edge joint and T-joint [12]. Most of these joints are prominent and can be identified as straight line edges in the image. Instead of requiring user to routinely click along these joints to create path, image processing methods to recognize geometrical patterns are applied to further simplify the teaching process. As shown in Fig. 6, user first defines a region of interest (ROI). Edge detection will be applied in the ROI after the extracted image is converted to gray-scale. Next Canny edge detection is used where a Gaussian kernel is applied to smooth out noises due to pixelation and workpiece surface texture prior to edge detection. Hough line detection algorithm is then performed to search for straight lines among edges found. These straight line edges are highlighted in green for user to select. The system would subsequently move the laser range finder to trace along the selected line path for targets creation. Parameters such as distance between via points can be specified by the user for better accuracy. The path creation using line detection facilitates the system to achieve pixel level accuracy in target point teaching as it eliminates potential human errors due to jerks and jitters while doing repetitive mouse clicking along the joint lines. Similar concept can be applied to paths of other geometrical form such as circular arcs and curves.

C. *Tool Orientation Teaching*

Besides accurate tool positioning, tool tip orientation teaching is another important aspect of industrial robot programming. Various processes such as welding, drilling and assembly require the robot to place the tool at not only orthogonal but sometimes at specific inclination angle with respect to working surface. It is difficult to teach such orientation in lead-through and walk-through teaching that relies solely on operator's observation. Our system incorporates the capability to teach tool orientation in three degree of freedoms. To realize this, three neighboring points, that are sufficient to describe a unique surface in the space, are chosen to define one teach point (refer to Fig. 7). With the first point defining the teach point position, the vectors to the other two points are crossed to find the local surface normal. User can further manipulate the tool tilt angle as well as roll angle in the AR environment. For a straight line path, only the starting point requires tool orientation to be specified whereas the following via points will adopt the same configuration. Tool vertical liftoff distance, which is critical in laser welding so as to focus the laser welding beam, can be taught as well. It involves a simple translation of the tool in its normal z-axis.

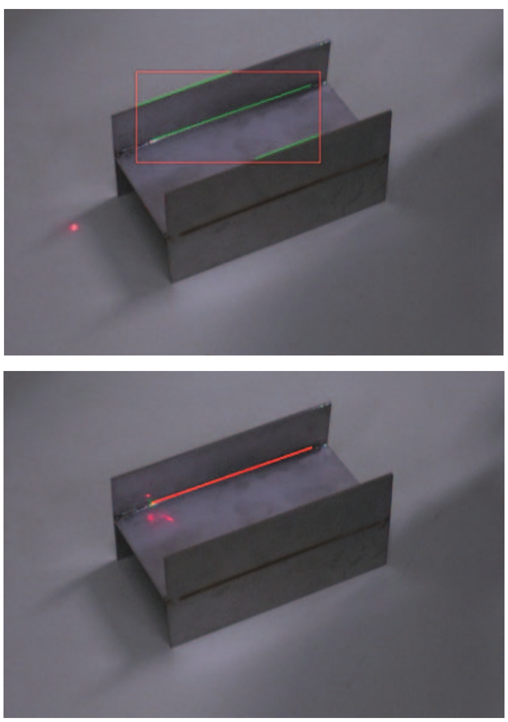

Figure 6: Path generation using line detection. Image on top shows the result of line detection in region of interest defined. Image at the bottom indicates the edge line selected.

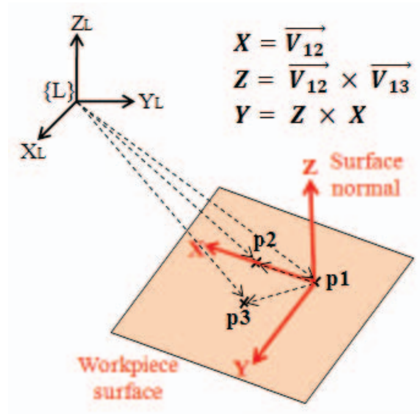

Figure 7: Use of Cartesian coordinates of three points on the surface to define the surface normal vector.

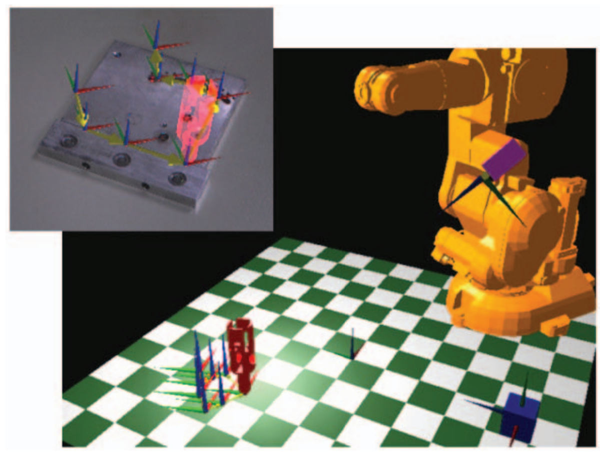

Figure 8: VR viewer

D. *Path Simulation in AR and VR Environemnt*

After the robot teaching, a simulation of the optimal path could be carried out to demonstrate how the tool would travel at specified orientation on the workpiece later. From Fig. 8, the simulation will be displayed in another simple VR viewer which is running concurrently with the AR environment. This VR viewer resembles offline programming environment. It offers user a better visualization of the tool depth information from the camera which could only be perceived by the shrinking in size of the rendered tool due to perspective effect in AR environment. The VR viewer also provides user with a complete understanding of the spatial relationship between robot, laser, camera, and workpiece.

IV. SYSTEM ACCURACY AND SOURCES OF ERROR

A set of experiments have been conducted using a ABB IRB 140 robot to evaluate the accuracy of the system. For this purpose, another laser range finder has been mounted at robot end effector, simulating the laser welding beam. The robot is commanded to position the laser range finder to ten test points on a workpiece. Besides measuring the planar positioning quality, the laser range finder mounted on the robot also provides a means to assess the accuracy of vertical surface liftoff distance of the tool. The result indicates that the maximum planar deviation from the commanded target points on the surface is limited to a precision of ±0.5mm. For liftoff distance wise, the system is capable of achieving an accuracy of ±1mm which is within the depth of focus of laser beam for welding.

There are several sources of error that can affect the accuracy of current system. Due to space constraints, the laser measurement unit is placed next to rather than on top of the workbench. Consequently the laser is always projected at a large incidence angle rather than normal to the target surface. This is unfavorable since it amplifies the signal to noise ratio (SNR) of the laser range measurement [13]. Besides that, there are also flaws in the calibrations to determine the pose of laser range finder relative to PTU in the laser measurement unit. More advanced calibration methods using accurate external sensor or self-calibration can be applied to compensate the abovementioned errors.

Another source of error includes low spatial resolution of laser measurement unit. It was found that the angular resolution of the PTU is 0.051^{o}. This is resolved into a finest step length of approximately 1mm when the laser is projected onto the workpiece surface during normal operation. This issue can be solved by either using a PTU with higher angular resolution or reducing the working distance between the laser measuring unit and workpiece. The image segmentation and centroid weighted sum estimation of image processing may not yield the laser spot true centroid location at all times. More advanced centroid calculation method that makes use of the shape of detected laser spot can help to reduce errors in image processing algorithm.

V. CONCLUSION

In this paper, an easy-to-use robot programming method which combines both the accuracy of laser range finder and intuitiveness of Augmented Reality (AR) has been presented. Unlike conventional AR, our system implementation does not need artificial marker to determine the position and orientation of the target point while performing virtual tool registration. The laser ranger finder of the measurement unit offers highly accurate depth information which is critical in many robotics operations. In our system, robot path teaching can be achieved by simple point-and-click or even line detection algorithm. Apart from tool positioning, orientation and liftoff distance from working surface of the tool tip can be taught through user's interaction with the virtual tool in the AR environment. Path simulation can be carried out in both AR and VR environment prior to robot execution. Currently, the system is capable of achieving a planar positioning accuracy of approximately ±0.5mm and vertical liftoff distance accuracy of ±1mm. The sources of error have been identified which there is room for further improvement on the teaching accuracy of the overall system.

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