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A Perceptive Vision-Based Robotic System Control to Increase Radiation Safety

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Controlling robots in hazardous working areas such as nuclear and radioactive spaces is a very hard mission where the operator is not in direct contact with the robot.The current research presents aperceptive Vision-based offline programming assisted by visual cues to intuitively (re)program robots and gives the operator the feeling of realism as if being existent in the working area. Picking and placing task is the target application where the position and orientation areestimated,and virtual graphics augmented on the image to provide the operator with virtual feedback. The workspace is monitored using a stereo camera which sends images to the PC for image processing. An experiment has been conducted using A 6 DOF arm robot to validate and evaluate the proposed methodandresults are compared with real measurements for error estimation.The algorithm has been applied using MATLAB/SIMULINK program to show the validity of the proposed system and prove its success.

Keywords: *Robotic arm kinematics, Radiation safety,*Radioactive environment,*Stereo-camera,Template matching,Pose and orientation estimation*

Introduction

Robots are developed basically to minimize the human effort in working and to increase the quality of work. They find their application in a variety of fields, one of which is the radioactive environment, generally prevailing in nuclear power plants. In nuclear science, the safety of operators has become motivation for robotic development. Appling robots in critical places like nuclear power plants is really worthy as there are benefits that can be derived from robot usage in such environments. [1-4].

Robots have been used to perform a wide range of tasks which would otherwise be time-consuming, strenuous and/or dangerous for the humans. Recent advances and developments in robotics led to the utilization of diverse types of robots in a large domain of applications. It has been reported that there is a strong recovery in the sales of industrial robots, and the installations of industrial robots will continue to increase in the next few years. Industrial robots often have little autonomous capability that needs to be re-programmed for a new task. Sometimes the cost of (re)programming exceeds the cost of robot installation. Finding a simple user interface for quicker, intuitive, and safer robot programming has been a challenging issue. Thus, there is an urgent demand to have a quicker, intuitive, and safer human-robot interface that uses the operator's common knowledge and addresses the drawbacks regarding the traditional programming methods to assist complex robots to solve unpredictable problems[5-9].Human-robot interface (HRI) can be defined as the interpretation and description of human intentions of the predicted task into a number of robot motions

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while taking the capabilities of the robot into consideration and the task requirements[10, 11].

According to the achievable degree of automation, robot programming methods can be classified into Manual, semi-automatic and Automatic programming. In manual programming, the user creates the robot program manually which is typically performed without the robot. The finished program is loaded into the robot afterward. It is time consuming, unintuitive, and poses safety concerns as it requires the presence of the operator within the workspace of the robot[12, 13]. Semi-automatic programming, on the other hand, is the case when the operators assist the robots to solve unexpected problems. This approach is what most industrial robotic systems embrace. Offline programming is a class of semi-automatic programming method where the program is generated apart from the real robot working environment space and then uploaded to the real robot in order to be implemented[14-16]. Virtual reality (VR) is used in offline programming where the workspace is needed to be fully simulated and this requires experts in simulation fields. This method is considered unintuitive as physical entities need to be modeled, calibrated and fine-tuned to compensate the discrepancies between the real environment and models[15-18].While in automatic programming, the user has little or no direct control over the program code that is generated from information obtained from a variety of indirect ways. It needs sophisticated software and hardware as well as developed infrastructure[10].

From 1990 to 1996 the European Commission conducted a research program, TELEMAN, with the aim to develop robots for use in radioactive environments, in particular with a view to the nuclear power industry. In 2013, the American Nuclear Society (ANS) presented an important report for engineers that contained some example applications of using robotics in radiation environments found in some past applications such as Fukushima nuclear power plant. Yan et al. (2015)[19] presented an industrial sorting system based on robot vision technology and introduced the main image processing methodology. Solyman, A.E., et al. (2016)[20] presented a complete research of using a vision-based controlled arm robot to collect the fallen hot Cobalt-60 capsules inside wet storage pool of industrial irradiator to increase radiation safety for industrial cobalt-60 irradiators.D.Ni., et al. (2016) [21]presented a user-friendly and intuitive robot programming interface for welding tasks. The task is remotely planned through the development of an augmented reality (AR) interface that is combined with haptic feedback and depth sensor is used to reconstruct implicit surfaces that represent the surfaces of work pieces

The aim of the work is to develop an effective offline human-robot interface (HRI), where the operator is not present in the working area for picking radioactive materials and placing them in a safe destination. Based on the proposed algorithm, the task is planned without a deep interference of the non expert operator in the field of robotics in technical calculations. Virtual cues and texts are usedto provide the operator with visual feedback to compensate the operator absence in the workspace. The rest of the paper is organized as follows: Section 2 briefly discusses the system overview and robot kinematics. Section 3 describes the methodology of the proposed method. Section 4 outlines the experimental Results and discussion. Lastly, Section 5 concludes the paper and proposes future research opportunities.

System Implementation

The setup of the proposed system is shown in Fig.(1). It includes a manipulator arm robot, an electrical gripper, a microcontroller, a laptop, a stereo camera, objects and hollow block representing radioactive material and safe place respectively. The following section describes briefly the system components.Fig.(1) describes the test rig used to accomplish the goal of the current research. The system consists of a 6-DOF arm robot with 6-revolute joints. The robot motions are achieved by the use of DC servo-motors. A gripper having the capability to manipulate small-size objects is attached at the end of the robot arm in such a way to facilitate moving the wrist in pitch and roll directions. The overall structure allows picking any regular object at arbitrary orientation on a plane surface. A fixed two web-cameras are used to capture the working environment. The images are sent to the laptop for image processing and running of vision algorithms. The position and orientation of the objects are then sent to a microcontroller type Arduino board based on ATmega2560 microprocessor. The microcontroller uses the robot inverse kinematic equations to generate the required signals to move the robot toward the objects, pick it up and move it to its target place. The next section discusses the forward and inverse kinematics of the proposed robotic arm and ends up with a series of equations relating to robot variables with object position and orientation.

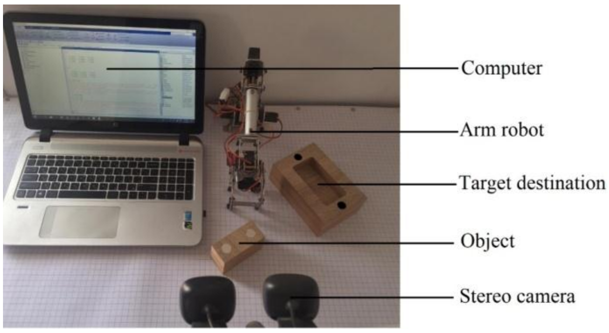

Figure (1): The proposed test rig

Robot arm kinematics

Given joint angles and link lengths of a robotic arm, forward or direct kinematics computes the end-effector position and orientation. This usually leads to a series of equations to be solved together. Figure 3 shows the arm robot layout and the different frames taken on it where, (0) denotes the base coordinate, (1) to (6) denote the coordinates of different arm joints. Figure 2 shows robot frames of a 6DOF robotic arm.

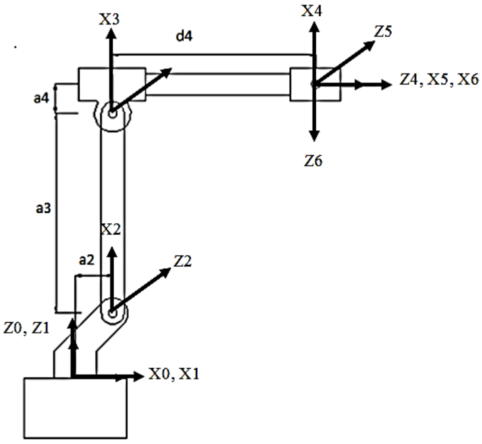

Fig. (2): robot frame system

After frame assignment, DH parameters (α_{i-1}, a_{i-1}, d_i, θ_i) are determined[22]. Table (1) shows the values of the DH parameters for the proposed robotic arm.

Based on these parameters, each joint frame (i) can be expressed relative to its preceding frame (i-1) using the general transformation matrix:

$$
{}^{i-1}_{\ \ i}T = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i\cos\alpha_{i-1} & \cos\theta_i\cos\alpha_{i-1} & -\sin\alpha_{i-1} & -\sin\alpha_{i-1}d_i \\ \sin\theta_i\sin\alpha_{i-1} & \cos\theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} & \cos\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Table (1): The D-H parameters for the designed robot

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	**0**	**0**	**0**	θ_1
2	**-90**	a_2	**0**	$-90+\theta_2$
3	**0**	a_3	**0**	θ_3
4	**-90**	a_4	d_4	θ_4
5	**90**	**0**	**0**	$90+\theta_5$
6	**-90**	**0**	**0**	θ_6

We can formulate the transformation matrix between every two successive frames as follow:

$$ {}^{0}T_{1}=\begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, {}^{1}T_{2}=\begin{bmatrix} s_2 & c_2 & 0 & a_2 \\ 0 & 0 & 1 & 0 \\ c_2 & -s_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$,{}^{2}T_{3}=\begin{bmatrix} c_3 & -s_3 & 0 & a_3 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, {}^{3}T_{4}=\begin{bmatrix} c_4 & -s_4 & 0 & a_4 \\ 0 & 0 & 1 & d_4 \\ -s_4 & -c_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$ {}^{4}T_{5}=\begin{bmatrix} -s_5 & -c_5 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ c_5 & -s_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, {}^{5}T_{6}=\begin{bmatrix} c_6 & -s_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_6 & -c_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Where $c_i = \cos \Theta_i$, $s_i = \sin \Theta_i$

In the inverse kinematic problem, the target is to find the manipulator parameters θ_1, θ_2, θ_3, θ_4, θ_5 and θ_6 to bring the tool frame (T) to coincide with the goal frame (G). Given the goal position relative to the station frame denoted as manipulator parameters can be solved according to equation 3

$$ {}^{0}T_{6}={}^{0}T_{1}.{}^{1}T_{2}.{}^{2}T_{3}.{}^{3}T_{4}.{}^{4}T_{5}.{}^{5}T_{6}={}^{0}T_{S}.{}^{S}T_{G}.{}^{G=T}T_{6} \quad (3) $$

The closed form solution of these equations is found to be:

$$ \theta_1 = \mathrm{Tan}^{-1}\left(\frac{p_y}{p_x}\right) $$

$$ \theta_3 = 2*\tan^{-1}\left(\frac{2k_3 \mp \sqrt{4*k_3{}^2-4*k_4{}^2+4*k_2{}^2}}{2*(k_4-k_2)}\right) $$

$$ \theta_2 = 2*\tan^{-1}\left(\frac{-2k_7 \mp \sqrt{4*k_7{}^2-4*k_8{}^2+4*k_6{}^2}}{2*(k_8-k_6)}\right) $$

$$ \theta_4 = \mathrm{Tan}^{-1}\left(\frac{s_1*a_x-c_1*a_y}{a_z*c_{23}+c_1*a_x*s_{23}+s_{23}*s_1*a_y}\right) \quad (4) $$

$$ \theta_5 = \cos^{-1}\left(\frac{a_z*c_{23}+c_1*a_x*s_{23}+s_{23}*s_1*a_y}{-c_4}\right) $$

$$ \theta_6 = \cos^{-1}\left(\frac{-a_x*s_{23}+c_1*n_x*c_{23}+c_{23}*s_1*n_y}{c_5}\right) $$

$a_x = -s_5*c_1*c_{23}-c_5*(s_1*s_4+c_4*c_1*s_{23})$

$a_y = c_5*(c_1*s_4-c_4*s_1*s_{23})-s_5*s_1*c_{23}$

$a_z = s_5*s_{23}-c_4*c_5*c_{23}$

$n_x = c_6*(c_5*c_1*c_{23}-s_5*(s_1*s_4+c_4*c_1*s_{23}))$
$+s_6*(c_4*s_1-s_4*c_1*s_{23})$

$n_y = c_6*\big(c_5*s_1*c_{23}+s_5*(c_1*s_4-c_4*s_1*s_{23})\big)-s_6*$
$(c_1*c_4+s_4*s_1*s_{23})$

$K_1 = c_1*p_x+s_1*p_y-a_2$

$K_2 = 2*a_3*a_4$

$K_3 = 2*a_3*d_4$

$K_4 = (d_4)^2+(a_3)^2+(a_4)^2-(k_1)^2-(p_z)^2$

$K_5 = c_1*p_x+s_1*p_y-a_2$

$K_6 = 2*a_3*p_z$

k_7 $K3 = 2*a_3*k_1$

$K_8 = (d_4)^2-(a_3)^2+(a_4)^2-(k_1)^2-(p_z)^2$

Where a_2, a_3, a_4, a_4, d_4 are links lengths, P_x, P_y and P_Z are the goal position relative to frame station frame (S).

System architecture

Figure (3) illustrates the architecture of the proposedmethod. The workspace image including the robot and the physical entities are first captured using the stereo camera and displayed through PC monitor. The human-robot interaction starts on the PC wherethe position and orientation of targeted object and destination can be defined using a mouse by simple clicks on interesting points on the image. From the pixel information chosen on the image, the 3D locations and orientations are estimated. Upon acquiring the3D pose and orientation, virtual cues are simulated and superimposed on the image as virtual feedback for the operator. According to the virtual feedback, the operator can modify or confirm the task for execution. When the task is confirmed, the commands are sent to the program compiler for code generation. The generated code is sent to the microcontroller which coordinates the signals sent to the robot servo motor to execute the intended task.

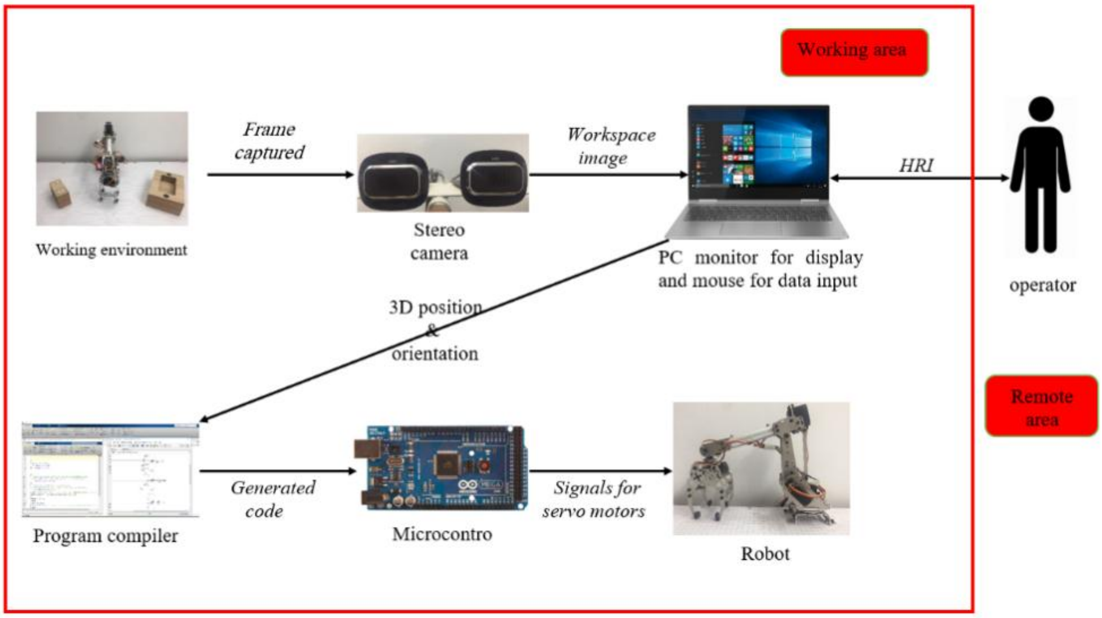

Fig. (3):System architecture

Methodology

The objective of the proposed methodology is to produce an offline robot programming method that enhances the effectiveness of the HRI for the operator to control an arm robot in a radioactive environment. Firstly, the user starts with camera calibration to obtain stereo camera intrinsic and extrinsic parameters. The workspace is displayed to the user through screen monitor. The user selects interesting points on the object and destination to estimate their location and orientation. To obtain the correspondence, the two images from left and right camera are rectified by applying the estimated rectification matrices on both images to reduce the search of features to 1D scanline which is the epipolar line and simplify the matching process. Template matching is applied, and the correspondences are obtained. The points and the correspondence are then multiplied by the inverse of the transformation matrices to obtain the location of pixels in the original images before rectification. Triangulation is then applied to obtain the 3D location of each chosen point on the image in cartesian space relative to the global coordinate system. Virtual entities are superimposed on the image indicating information about the expected task to support the operator with visual feedback to give a feeling of realism as if the operator is in direct contact withthe working environment for task modification or confirmation. After operator confirmation, the code is generated and sent to the microcontroller. The microcontroller converts the generated code into signals for task implementation.

Template matching

Matching is an operation offinding a set of points in one image which can be identified as the same points in another image. Template matching is anintensity-based matching method which works by sliding the template from the reference image which is usually smaller than the image across the targeted image. As it slides, it compares the template to the portion of the image directly under it depending on the information provided by the neighboring pixels. Most template matching applications commonly use the cross-correlation methods such as SSD (Sum of Squared Differences), SAD (Sum of Absolute Differences) and NCC (Normalized Cross Correlation) to determine the best match**.**The SSD method costs computationally compared to SAD. NCC is usually used to overcome the problem of illumination change between the two cameras according to Equation 5[23-25].

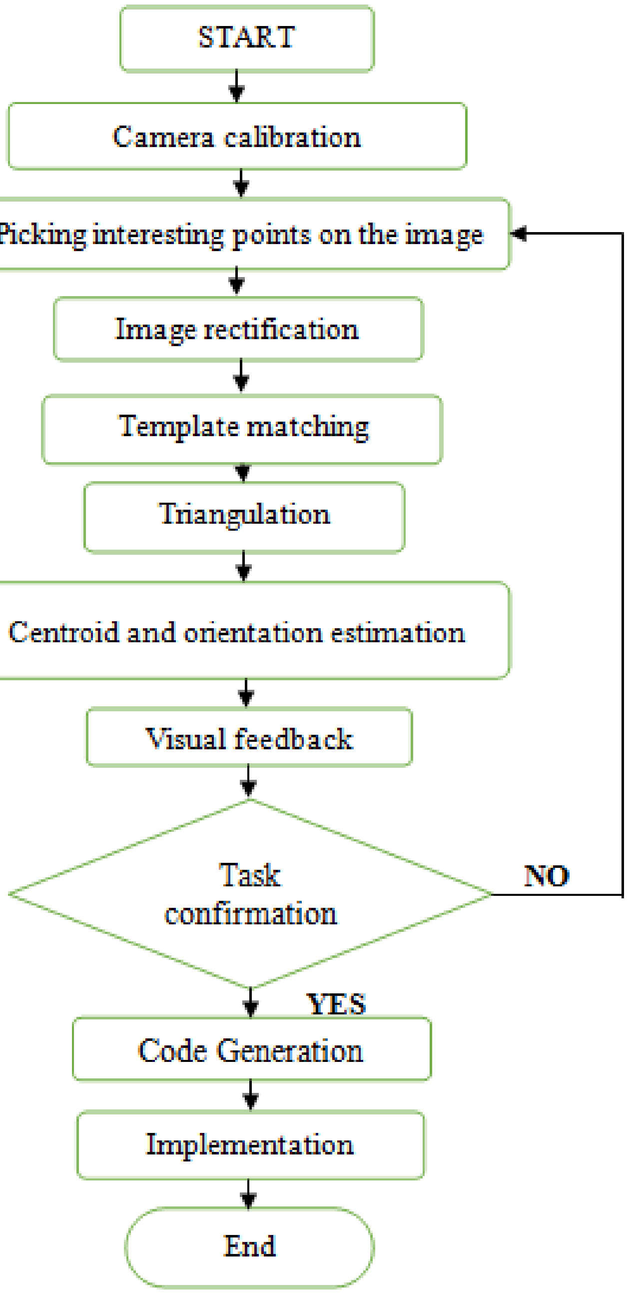

Fig. (4):Proposed system methodology

$$\mathrm{NCC}(x, y) = \frac{\sum_{j=0}^{N-1} \sum_{i=0}^{M-1} I(x+i, y+j).T(i, j)}{\sqrt{\sum_{j=0}^{N-1} \sum_{i=0}^{M-1} I(x+i, y+j)^2}.\sqrt{\sum_{j=0}^{N-1} \sum_{i=0}^{M-1} T(i, j)^2}}$$

Where W and H arethe size of the image I, M and N the size of template T and x and y are the template location. Sliding the template across the whole image, which is called exhaustive search costs probability of obtaining wrong matches. So, constraints are needed to reduce the size of the search space[26].

3.2Stereo image rectification

Image rectification is an image transformation processused to bring two images captured at different positionsto a common image plane by applying 2D projective transformations.

computationally, where the comparison is applied for each pixel in the image and increase the

The images are simulated as if the two cameras are rotated so that the corresponding epipolar lines of the two images coincide and become parallel to the baseline and two coplanar images are generated. It is a good pre-processing step for dense matching algorithms such as template matching as It restricts the search domain for each match to a line parallel to the x-axis and this speed up matching. The two pair of images are rectified where the transformation matrices for the two images are estimated and applied on the images according to Equation 6[27-29].

$$T_i = K_n R_n R_i^T K_i^{-1}$$

Where $K_n = \frac{1}{2}(K_1 + K_2), R_n = \begin{bmatrix} r_1^T \\ r_2^T \\ r_3^T \end{bmatrix},$

$$r_1 = \frac{C_2 - C_1}{\|C_2 - C_1\|},$$

$$r_2 = \frac{\underline{K} \times r_1}{\|\underline{K} \times r_1\|},$$

$$r_3 = r_1 \times r_2, \underline{K} = R_1^T \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \qquad (6)$$

T is the transformation matrix, K is the intrinsic parameter, R is the rotation matrix and C is the translation vector.

Template matching algorithm is applied to the rectified images obtaining the corresponding point. The locations of pixels obtained are multiplied by the inverse of the transformation matrices to obtain the location of pixels in the original images before rectification.

Triangulation

Triangulation is the task of computing the 3D position $\overline{X}$= (X, Y, Z) of pixels on the image by forming atriangle according to the linear equation 7. Given calibrated stereo camera and pixels on the image with correspondences, the 3D location in Euclidean coordinate system is estimated by solving the linear equation. Singular value decomposition (SVD)is used to find the eigenvector which corresponds to the smallest singular valuewhich is the point location in 3D[30, 31].

$$\begin{bmatrix} y p_3^T - p_2^T \\ p_1^T - x p_3^T \\ y' p'^T_1 - p'^T_2 \\ p_1^T - x' p'^T_2 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = 0 \qquad (7)$$

Where x, y is the pixel location on the image and X, Y, Z is the point location relative to the camera coordinate system.

Virtual cues model registration

As illustrated before, working with radioactive elements poses safety concerns to the operator, and it is hard to control the robot intuitively especially when the operator is far away from the working environment. When the operator clicks interesting points on the object and destination on the image, the location and orientation of both are estimated. Virtual graphics are appliedto the image to ease the task of programming the 6 DOF arm robot to complete the task of picking a radioactive element and placing in the target safe place. Virtual text appears on the image showing the location of the object and destination in world coordinate and an arrow starting from the object where the picking will occur pointing at the destination where the object will be placed to place. The visual feedback provides the user with a sense of realism and awareness of the predicted task to be executed. The 3D position (X, Y, Z) of the element and destination can be edited manually by the operator and the virtual arrow is edited according to the operator's modification until the task is confirmed.Figure (5) illustrates the working environment monitored by a stereo camera and displayed on a PC computer with virtual feedback waiting for the operator task confirmation to be executed.

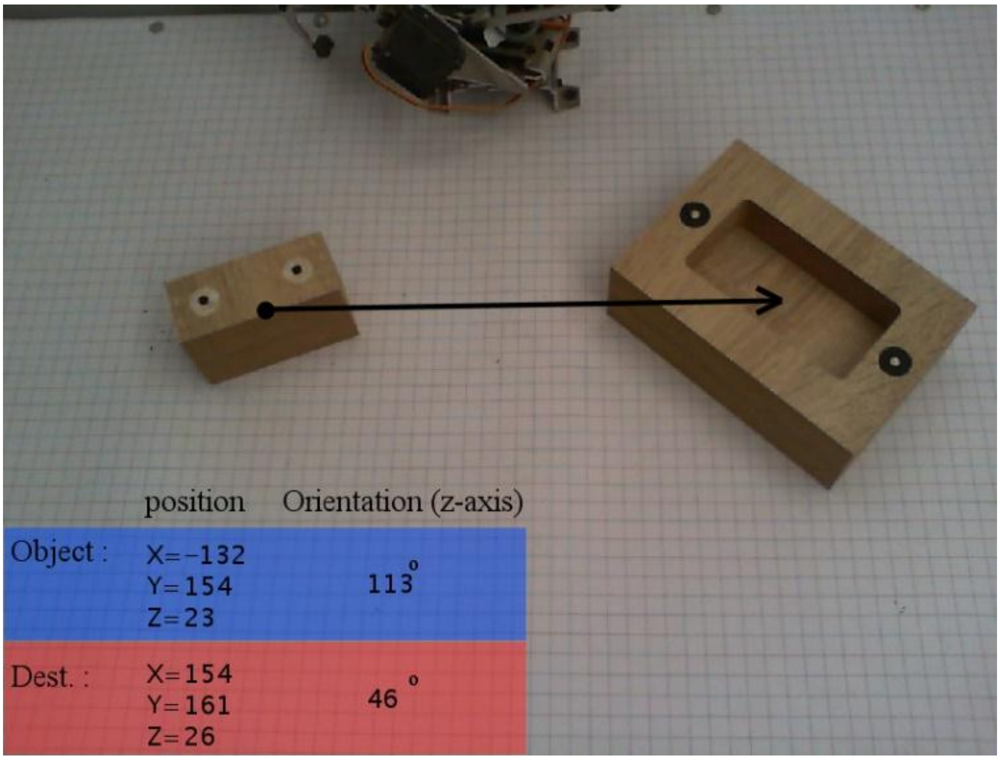

Figure (5):Image of the expected task supported by virtual graphics and texts

Results and Discussion

A pick and place case study has been implemented on the proposed interface for intuitive HRI for a robot programming in radioactive environments where the operator cannot be existed in the workspace.The system performance was studied using a single pair of cameras installed at 1.3 m away from the workplace, 9x 4 x5.4 cm object represents a radioactive material, 10.5x5.5x5.4 cm hollow block represents the targeted safe place and arm robot for task execution. The HRI starts with the interaction between the operator and the image where the colored circles on the object and destination are clicked on the image, both position and orientation are estimated. virtual cues are superimposed on the image in form of an arrow and virtual texts providing the operator with virtual feedback to assure that the task will be performed as planned.The task has been implemented and the position and orientation results were compared to the actual measurements.The mean error of position estimation is(9.4) mm and the standard deviation is (6.47) and for orientation, the mean error is (1.2) degree and the standard deviation is (1.95) degree.

Conclusion and Recommendations

In this study, a brief review of the application of robots in hazardous and radioactive environments and the problems of programming industrial robots are presented. A simple user interface for effective HRI is proposed with the aid of virtual cues superimposed on the image to fill the gap of operator's absence in hazard an unsafe working environment as if the operator exists in the working area. A case study is conducted to validate the method. The stereo camera is used to send images of the working environment to PC computer; images are rectifiedand template matching is applied to obtain matching points. 3D location is obtained, and position and orientation are estimated. The method uses information from stereo camera images and the operator's interaction with these images to complete the task successfully. Graphical information is overlaid on the image for the operator waiting for modification or task confirmation. The system has been implemented, tested and evaluated and the overall results show that the proposed HRI system has advantages which encourage upgrading. First, the proposed method is intuitive, and the operators are able to learn and perform the task without deep interference in the mathematical calculation of position and orientation. Second, the visual cues support the operator with feedback to help for modification when the simulation is not satisfactory or confirmation of the intended task. In the future, a number of areas can be further explored and developed to improve the HRI interface. A better method can be developed to improve the performance where obstacles can be taken into consideration not only for the EE but also for each link of the robot**.**

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