AC 2007-1075: REMOTE QUALITY CONTROL INTEGRATED WITH INTERNET-BASED ROBOTIC SYSTEMS

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Remote Quality Control Integrated with Internet-based Robotic Systems

Abstract

The current trends in industry include an integration of information and knowledge base network with a manufacturing system, which coined a new term, e-manufacturing. From the perspective of e-manufacturing, any production equipment and its control functions do not exist alone, instead becoming a part of the holistic operation system with distant monitoring, remote quality control and fault diagnostic capabilities. The key to this new paradigm is the accessibility to a remotely located system and having the means of responding to a rapidly changing environment. In this context, this paper presents innovative methods in remote part tracking and quality control using the Ethernet SmartImage Sensor and the Internet controllable Yamaha SCARA robot. The accuracy of the proposed scheme has been verified and subsequent quality control functions have been integrated, which vindicate the industrial applicability of the setup. The paper also discusses some of the online experiments conducted by the students and presents the evaluation outcomes. The experiment results suggest that online laboratory learning can be substantially enhanced by the use of even the simplest form of artificial graphical information and most students prefer having an instructor present even the lab is taught online. The implications from this study can be used to benefit many schools that begun offering online lab courses.

I. Introduction

A current trend for manufacturing industry is shorter product life cycle, remote monitoring/control/diagnosis, product miniaturization, high precision, zero-defect manufacturing and information-integrated distributed production systems for enhanced efficiency and product quality[1-6]. In tomorrow's factory, design, manufacturing, quality, and business functions will be fully integrated with the information management networks[7-9]. This new paradigm is coined with the term, e-manufacturing. In short, ''E-manufacturing is a system methodology that enables the manufacturing operations to successfully integrate with the functional objectives of an enterprise through the use of Internet, tether-free (wireless, web, etc.) and predictive technologies[10, 11]''. Other characteristics may include emergence, intelligence, non-deterministic, complexity, and self-organization in the enterprise system[12]. One of the enabling tools to realize the e-manufacturing is the ability to predict the variations and performance loss[11]. Therefore, Internet-based gauging, measurement, inspection, diagnostic system, and quality control have become critical issues in the integration with e-manufacturing systems and management[10, 11].

For manufacturing industry, the current emphasis on quality, reliability and the competitive state of the international/domestic markets have resulted in both greater visibility and increased responsibility for quality and inspection[13]. According to the white papers from the American Society for Quality and the U.S. Department of Labor, 2004-2005 Edition on Bureau of Labor Statistics[14, 15], increased emphasis has been placed on quality control in manufacturing, while inspection is more fully into production processes than in the past [16, 17]. The recent progress in developing new, automated production and measuring instrument has led to the 100 % real-time inspection, where critical dimensions are measured and verified while parts are being produced[18-25].

The immediate benefit from this approach is the reduction of manufacturing cost, by preventing further processing of defective parts along the manufacturing stages. More importantly, the remote accessibility and the ability to control the equipment over the Internet/Ethernet/LAN present unprecedented benefits to the current manufacturing environment.

In this context, the main focus of this paper is to use the Internet as an infrastructure to integrate manufacturing with quality for industrial applications [26-32], as shown in Figure 1. This Internet-based quality control scheme is called "E-Quality for Manufacturing" or EQM for short. By its definition, EQM refers to the holistic approach to design and to embed efficient quality control functions in the context of network integrated manufacturing systems with the use of advanced sensor technology. The aim is to achieve real-time, fully automated quality inspection, which is better suited for a modern production environment. Additionally, this study investigates how cognitive learning of remotely located systems develops under varying modalities. This was attained through three specifically defined research objectives: (1) study the effects that the audio-visual modalities and their properties have on the understanding of remote systems; (2) study the effects the visual augmentation have on the spatial cognition, spatial visualization and interaction with remote systems; and (3) study the effects the lack of instructors have on online learning.

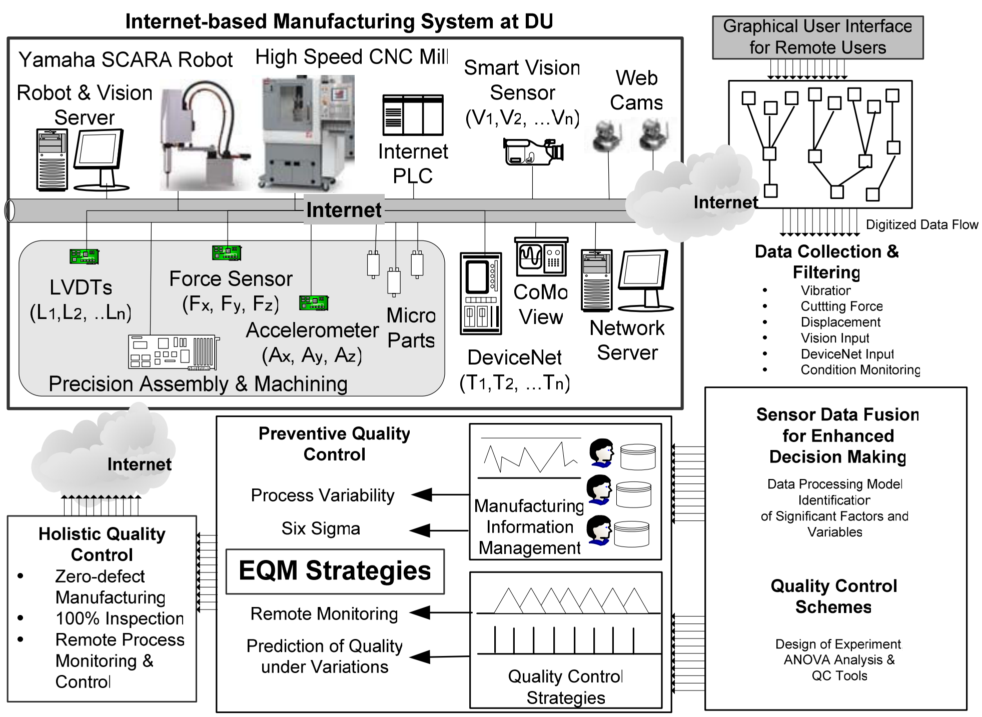

Figure 1. The proposed concept of EQM within the framework of Internet-based manufacturing systems developed at Drexel University.

II. Development of Internet-based Systems

To realize the notion of EQM into industry applicable strategies, some of the highly advanced production equipment, all of which can be accessed through their unique IP addresses, has been integrated within the Drexel's LAN networks in the form of Internet-based systems. The SmartImage vision system from DVT Company is Ethernet-based and self-contained with a lens, a LED ring lighting unit, FrameWork software, and an A/D converter. The camera can be accessed over the network through its IP address and a port number. Any image processing, inspection and quality check can be performed remotely and instant updates on system parameters are possible. The camera contains a breakout board with eight I/O ports, which can be hardwired for transmitting 24-V signals based on the quality control criteria (i.e., Fail, Pass, and Warning). Also, descriptive statistics can be sent over the network in the form of text string using a data link module (e.g., number of features, area, axis, pixel values, and other user defined characteristics). A Kistler CoMo View Monitor has connectivity with sensors, including a high sensitivity force transducer for micro scale assembly force analysis and a linear variable displacement transducer (LVDT) for dimensional accuracy check with one micron repeatability. The CoMo View Monitor is web-accessible, hence web-enabled sensor networks for quality control is feasible. The Yamaha YK 250X SCARA (selective compliance assembly robot arm) robot is specifically configured to have a high rigidity along the vertical axis, while compliant along horizontal directions in the form of swing arm motions[33]. This renders the robot particularly suitable for pick and place or assembly operations with a high degree of accuracy and speed. For part handling, a variable speed Dorner 6100 conveyor system is connected with robot's I/O device ports in order to synchronize the conveyor with the motion of robot.

The robot's RCX 40 controller is equipped with an onboard Ethernet card, an optional device for connecting the robot controller over the Internet. The communications protocol utilizes TCP/IP (Transmission Control Protocol/Internet Protocol), which is a standard Internet Protocol. The unit uses 10BASE-T specifications and UTP cables (unshielded twisted-pair) or STP cables (shielded twisted-pair) can be used. PCs with Internet access can exchange data with the robot controller using Telnet. Once the connection is established, programming and controlling of robot can be conducted remotely. One drawback to this approach is the lack of auditory/visual communications between the robot and remotely situated operators. To counter this problem, the Telnet procedure has been included in the Visual Basic codes to develop an application program interface (API), including windows for the robot control, machine vision, DLink DCS-5300 web camera, and online part tracking (Figure 2). The API improves not only the visualization of robot operations in the form of an intuitive interface, but also provides enhanced controllability to the operators. The API can verify the robot coordinate points, once the robot has been driven to the vision guided locations. The API monitors the current robot position, and decides the best approach as the vision sends the part coordinates to the robot.

III. Online Vision Guided Tracking

The work presented in this study addresses one of the most common problems in vision guided robotic tracking with minimum technical complications for ease of industrial applications. The alignment between the image planes and robot coordinate systems has been a challenging task, involving lengthy derivation of complex mathematical relationships. This type of setup is susceptible to minor changes that frequently occur in production environment[34-39]. The methodology developed in this study emulates production environment, utilizing the Internet-based robot and the vision sensor without highly complicated mathematical calibrations. The image captured by the camera and the robot working space directly over the conveyor are considered as two horizontal planes. These two planes are considered parallel, hence any point on the image plane (denoted as a_i and b_i in Figure 3) can be mapped into the robot plane.

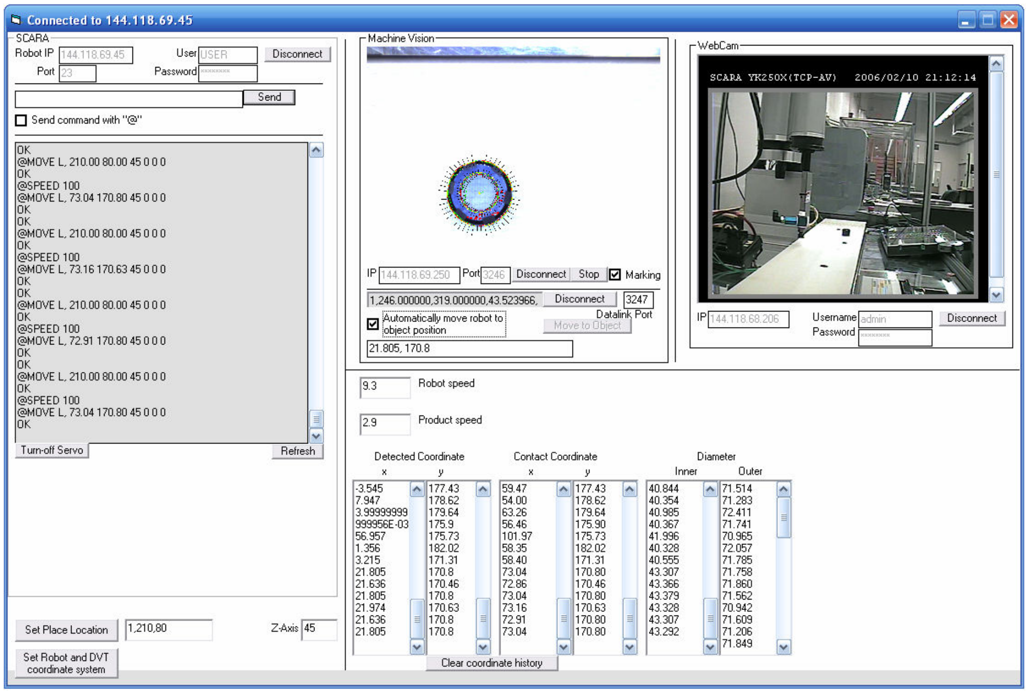

Figure 2. Snapshot of the API developed for EQM.

By operating individual values of a_i and b_i with the scale factors S_x and S_y, the image coordinates (pixel coordinates) can be translated into the robot coordinates using the following functional relationship[40]:

$$f : \mathbf{P_i} \triangleq \mathbf{R_i} + \mathbf{S_i} \cdot \mathbf{v_i} + \boldsymbol{\varepsilon}_\mathbf{i}\,, \tag{1}$$

where $\mathbf{P_i}$ = the robot state vector at time i, $\mathbf{R_i}$ = the robot coordinate vector at the origin of the image plane, $\mathbf{S_i}$ = the scale vector with 2 x 2 block of the form $\begin{bmatrix} S_x & 0 \\ 0 & S_y \end{bmatrix}$, $\mathbf{v_i} = [a_i, b_i]^T - [a_0, b_0]^\mathbf{T}$, and $\boldsymbol{\varepsilon}_\mathbf{i}$ = a zero mean Gaussian error vector due to coordinate mapping. The robot state vector assumes a form[40]:

$$\mathbf{P_i} = \left[\mathbf{x}, \dot{\mathbf{x}}, \mathbf{y}, \dot{\mathbf{y}}, \mathbf{z}, \dot{\mathbf{z}}, \phi, \dot{\phi}, \theta, \dot{\theta}, \psi, \dot{\psi}\right]^\mathbf{T}, \tag{2}$$

where x, y, z = the translated robot coordinates (mm) from the pixel or image coordinates, ϕ, θ, ψ = the relative orientation described by roll, pitch, and yaw angles, and $\dot{\mathbf{x}}, \dot{\mathbf{y}}, \dot{\mathbf{z}}, \dot{\phi}, \dot{\theta}, \dot{\psi}$ = the relative velocities. Considering the work area as a 2D surface, the scale factors for each axis can be represented as:

$$S_x = \left[\frac{(x_1 - x_r)^2 + (y_1 - y_r)^2}{(a_1 - a_0)^2 + (b_1 - b_0)^2}\right]^{1/2}; \quad S_y = \left[\frac{(x_2 - x_r)^2 + (y_2 - y_r)^2}{(a_2 - a_0)^2 + (b_2 - b_0)^2}\right]^{1/2} \tag{3}$$

The goal is to minimize the transformation error caused by lens distortion and other minor misalignments between the planes:

$$\Theta_{\min} \le \boldsymbol{\varepsilon}_\mathbf{i}(\mathbf{x,y}) \approx \max[(\hat{\mathbf{P}}_\mathbf{i}(\mathbf{x}) - \mathbf{P(x)}), (\hat{\mathbf{P}}_\mathbf{i}(\mathbf{y}) - \mathbf{P(y)})] \le \Theta_{\max}\,, \tag{4}$$

where $\mathbf{P_i}$ = the true location, $\hat{\mathbf{P}}_\mathbf{i}$ = the observed robot position over the networks, and Θ_{min} & Θ_{max} = the preset limits for the magnitude of errors in accordance with the focal length. This was done by dividing the region captured by the camera into (*m* x *n)* grid, and applying separate scaling factors for better accuracy. For the points on the grid and along the coordinate axes of the camera, the robot Cartesian coordinates are taken as the reference. Figure 3 shows the division of the image captured by the camera into an array. The division of image plane into equally spaced blocks increases the accuracy of the system by countering the problems in: (1) the image plane cannot be perfectly aligned with the robot coordinate axes, which is the case in most industrial applications; and (2) the perfect alignment requires a host of expensive measuring instruments and a lengthy setup.

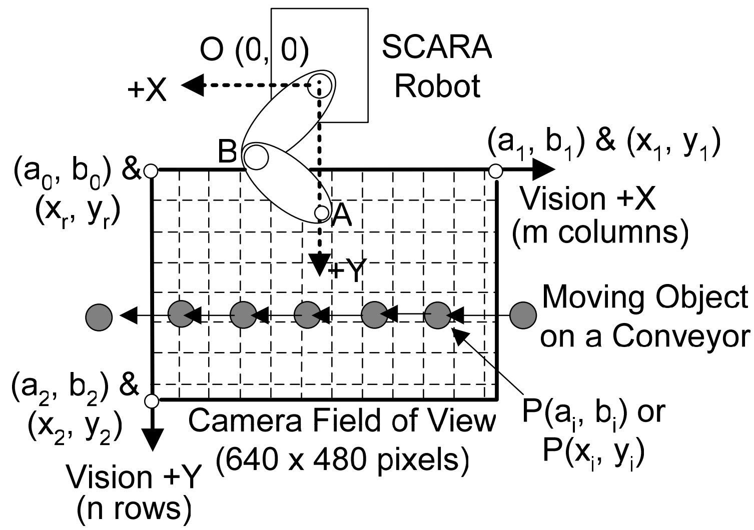

Figure 3. Coordinate system for machine vision (a, b) and SCARA robot (x, y).

The scale factors consider the robot Cartesian coordinates at every intersection of the grid lines. Therefore, any point detected within the image plane will be scaled with respect to the increment in the grid from the origin. The area of a moving object is defined in the form of [40, 41]:

$$A_d(mm^2) = \chi \cdot \psi \cdot \sum_a \sum_b I(a,b)\,, \tag{5}$$

where $\chi =$ the calibrated pixel size (mm) along vision X axis, $\psi =$ the calibrated pixel size (mm) along vision Y axis, and

$$I(a,b) = \begin{cases} 1 & \textit{if intensity of pixel at } (a,\ b) \ \geq \ \textit{threshold} \\ 0 & \textit{otherwise} \end{cases}\,, \tag{6}$$

The center point of moving object (centroid), which is a pick up location for the robot, is defined as:

$$Ctr_x = K^{-1} \cdot \sum_{k=1}^{K} \left[Xe_k - Xs_k \right] \cdot 2^{-1}; Ctr_y = G^{-1} \cdot \sum_{g=1}^{g} \left[Ye_g - Ys_g \right] \cdot 2^{-1}\,, \tag{7}$$

where *K and G* = the total number of pixel rows and columns in the object, respectively, *Xe* = the x coordinate point for a left most pixel in row *k*, *Xs* = the x coordinate point for a right most pixel in row *k*, *Ye* = the y coordinate point for a bottom pixel in column *g*, and *Ys* = the y coordinate point for a top pixel in column *g*. Let $P(a_i, b_i)$ be the center point of the moving object detected, then the following equations translate it into:

$$\begin{aligned} x_i &= x_r + \sum_{n=1}^{p-1} S_{x,n} \cdot \left|a_n - a_{n-1}\right| + S_{x,p}\left[a_i - a_{p-1}\right] + \varepsilon_x; \\ y_i &= y_r + \sum_{m=1}^{q-1} S_{y,m} \cdot \left|b_m - b_{m-1}\right| + S_{y,q}\left[b_i - b_{q-1}\right] + \varepsilon_y \end{aligned}, \quad (8)$$

where n = the number of columns, m = the number of rows, *p and q* = the number of grids from the origin where $P(a_i, b_i)$ is located, and ε_x & ε_y = imprecision involved in the scaling. In order to capture the moving objects on a conveyor, a series of images is taken at a fixed rate of 75 frames per second and the time interval between each frame is calculated. The algorithms in the API automatically detect the center of moving object and translate that into robot coordinates. The speed of the object is defined as:

$$\lambda_P(mm/s) = \|\mathbf{u} - \mathbf{v}\| \cdot t_f^{-1} = \left[(Ctr_{x,f} - Ctr_{x,f-1})^2 + (Ctr_{y,f} - Ctr_{y,f-1})^2\right]^{1/2} \cdot t_f^{-1}, \quad (9)$$

where $\mathbf{u} = (Ctr_{x,f}, Ctr_{y,f})$, the centroid of the object at frame no. *f*, $\mathbf{v} = (Ctr_{x,f-1}, Ctr_{y,f-1})$, the centroid of the object at frame no. *f-1*, and t_f= the time taken for the part to travel from frame no. *f-1* to frame no. *f*. The API calculates the speed of the moving objects, then coincides the robot speed. Once a part is detected, a future coordinate point where the part to be picked up, is determined by the API. This information is automatically transmitted to the robot controller, and the robot moves to pick up at the designated location. Therefore, the robot travel time to reach the future coordinate must coincide with the time taken by the part to reach the same coordinate. The reach time t_r (ms) is defined in the form of:

$$t_r = \left[\sum_{f=2}^{h} \|\mathbf{u} - \mathbf{v}\|\right] \cdot \left[\|\mathbf{u} - \mathbf{v}\| \cdot t_f^{-1}\right]^{-1} = \left[(x_i - x_r)^2 + (y_i - y_r)^2\right]^{1/2} \cdot \lambda_r^{-1}, \quad (10)$$

where *f* = the frame number, indicating the first frame from which the vision system detects the center of moving object, *h* = the frame number at a pick up location, x_i & y_i = the coordinate of the pick up location, and λ_r = the robot speed (mm/s). Under different speed settings, the accuracy analysis of pick up operations was performed and the results are illustrated in Figure 4. Two different speed combinations of robot and moving object were selected based on the range of operations usually performed on the system. The percentage error was defined as the deviation between the vision generated coordinates and actual robot coordinates at the pick up location, in the form of:

$$\%Error = \max\left[(x_i - Ctr_{x,f}) \cdot x_i^{-1} \cdot 100,\ (y_i - Ctr_{y,f}) \cdot y_i^{-1} \cdot 100\right] \quad (11)$$

The speed settings selected for the testing did not seem to affect the errors in any noticeable way. The plot shows a random pattern, indicating no systematic error.

IV. E-quality for Manufacturing

With all the recent concerns in the United States about domestic jobs going overseas, many companies have been outspoken about relying on quality as a competitive strategy for keeping jobs at home[14, 42]. Ford Motor Company stated in 2003 that it had saved $1 B through waste elimination since the start of its quality control effort in 2000. To enhance the manufacturing quality of product that requires constant vigilance, state-of-the-art technologies including lean (high-tech) manufacturing, robots and automation, and other quality-enhancing techniques must be implemented in manufacturing factories. The example shown in Figure 5 is the cap of the CNC tool holder specifically designed for high speed machining applications according to the ISO 20 standards of dimensional tolerance. The cap constrains the high precision collet (ER16-HP5 from Jabro Tool Co. with 0.0002-in precision) and rotates at a high speed, hence the dimensional integrity for dynamic balance is of critical importance.

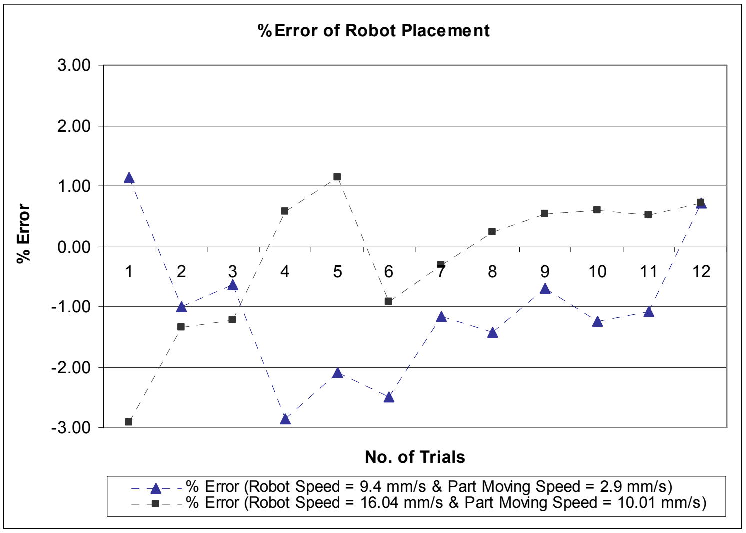

Figure 4. Graph showing the % error between robot versus vision generated coordinates.

Two parameters, the inside and outside diameters, have been selected as the variables of interest, then remotely monitored and inspected. Once the camera captures the part, a series of image processing routines was applied. The part was first isolated from the background using a Blob Sensor (with a 50% pixel intensity threshold), then its contrast was enhanced and white noises were reduced. The Circle Measurement Sensor was used to detect the inner and the outer circles of the part, and the corresponding measurement data were sent to the API.

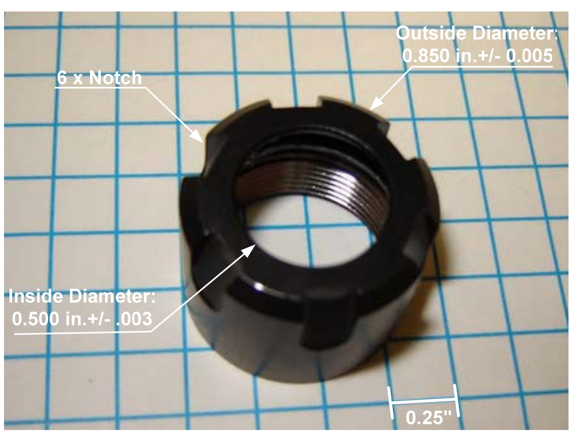

Figure 5. A sample part for remote quality control.

The evaluation criterion follows the principles of multivariate statistical analysis. The correlation between two variables [43]. The parts are evaluated in tune with the quality measurement criterion and become rejected upon exceeding a preset value. The preset values are aligned with the design specifications of dimensional tolerance. The sample part being examined should assume the range of values, [0.845-in. (21.463 mm), 0.855-in. (21.717 mm)] for outside diameter and [0.497-in. (12.624 mm), 0.503-in. (12.7762 mm)] for inside diameter. If any part fails to pass the criterion, the robot picks the part up from the conveyor and drop them in the sorting bin for bad parts. Good parts are carried away by the robot into another sorting bin for subsequent operations. The discrepancy between the vision generated pick up location and the actual robot coordinate was measured using the following equation:

$$Error(mm) = \left[(Ctr_{x,f} - x_i)^2 + (Ctr_{y,f} - y_i)^2 \right]^{1/2}, \quad (12)$$

The graphical expression is given in Figure 6, where the data points show a random characteristic.

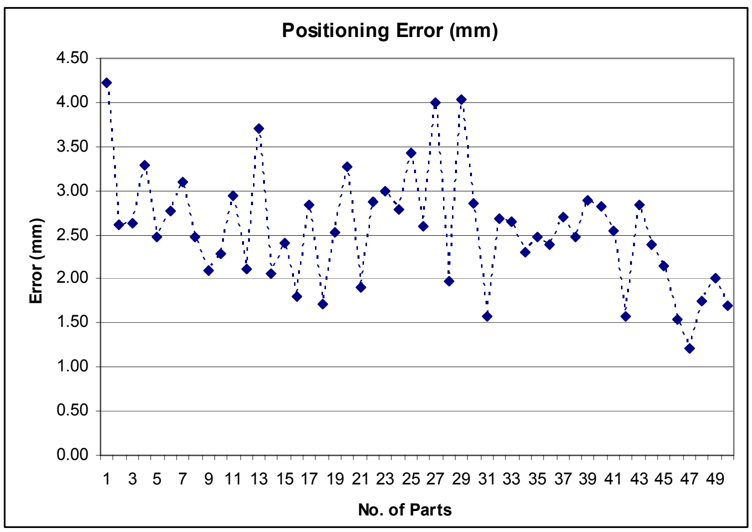

Figure 6. A graphical representation of robot positioning error.

V. Online Experiments

A new lab course, MET 380 Robotics & Mechatronics, was offered in the fall term of 2005 at Drexel University. In the class, students in MET 380 spent 8 weeks on laboratory experiments in order to get familiar with the topics in robot workings, operations, programming, and sensor integration. Experiments utilized three Yamaha robots for pick & place operations, a machine vision system for part inspection, web cameras for monitoring, and integration of various sensors. The web cameras sent image sequence to the remote users. With the built-in microphones, auditory feedback was also provided to the students. The last two weeks of course were dedicated to the specifically designed online robotic experiments. As depicted in Figure 7, the experiments involved two web cameras for front and side viewing. The students, sitting remotely from the robot, were asked to use the two viewing windows on a PC and to command the robot to move onto the pick point, followed by the place point. The vacuum suction cup was to be positioned directly over the two points in order to measure the positioning accuracy. The exact coordinates of two points were recorded prior to the experiments, and the students were asked to record their robot's positions for each point. The overall time to complete the task was also measured. In order to provide additional graphical information, a simple form of arrows corresponding to the orientation of robot's +X & +Y axes was provided. The viewing windows, therefore, provided the live image streams of the robot operations as well as the graphical representation of robot's axes. The experiments demanded constant visual attention from the operators, due to the lack of depth perception.

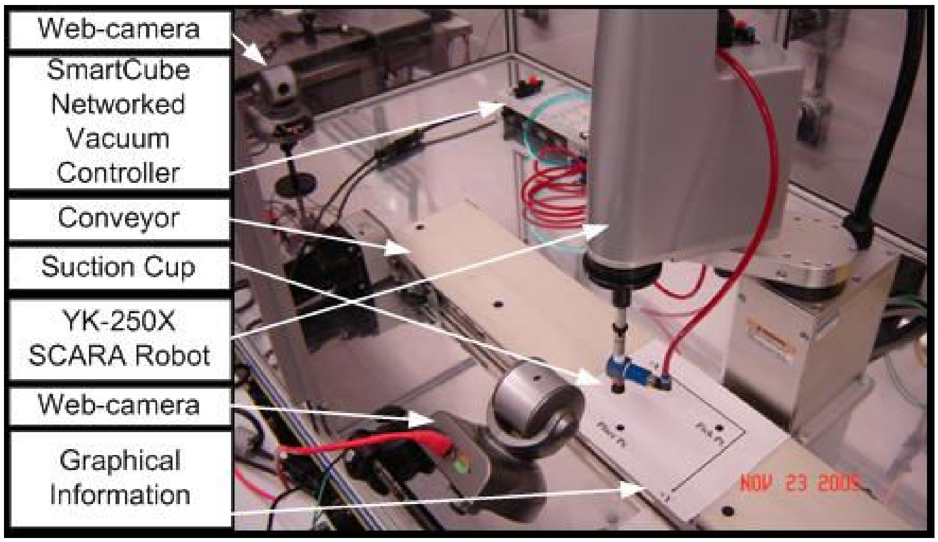

Figure 7. Experimental setup for online laboratory exercise.

VI. Assessment & Outcome

With the increasing number of new and complex technologies that can be used in distance learning, there is a need for an effective assessment in the use of new technologies for distance education. As suggested by Clark[44], the authors developed assessment questionnaire with a separate consideration of user interface as well as delivery and instruction technologies. The assessments were designed to extract students' opinions on the visual modality, the augmented reality in remote operation, the delivery and instructional technologies in online lab. The students were formed into two groups, each consisting of 13 students. The first group conducted the experiments using two viewing windows (web-cam images) and a teach pendant for robot control. Students have been using a teach pendant in the previous experiments, hence they are accustomed to the workings of teach pendant. The second group used the same viewing windows on a PC but with a computer based robot control interface that they have never used before (Figure 8). By changing the mode of robot control, the first group is only exposed to a different visual/audio modality (present vs. tele-present), while the second group is exposed to not only the shift of visual/audio modality but also the control method. Each group received the customized questionnaire right after the online experiments. The first set focused on the adequacy of visual/audio modality and the effects of augmented reality. The second set was intended to evaluate the comparison between the delivery and instructional technologies.

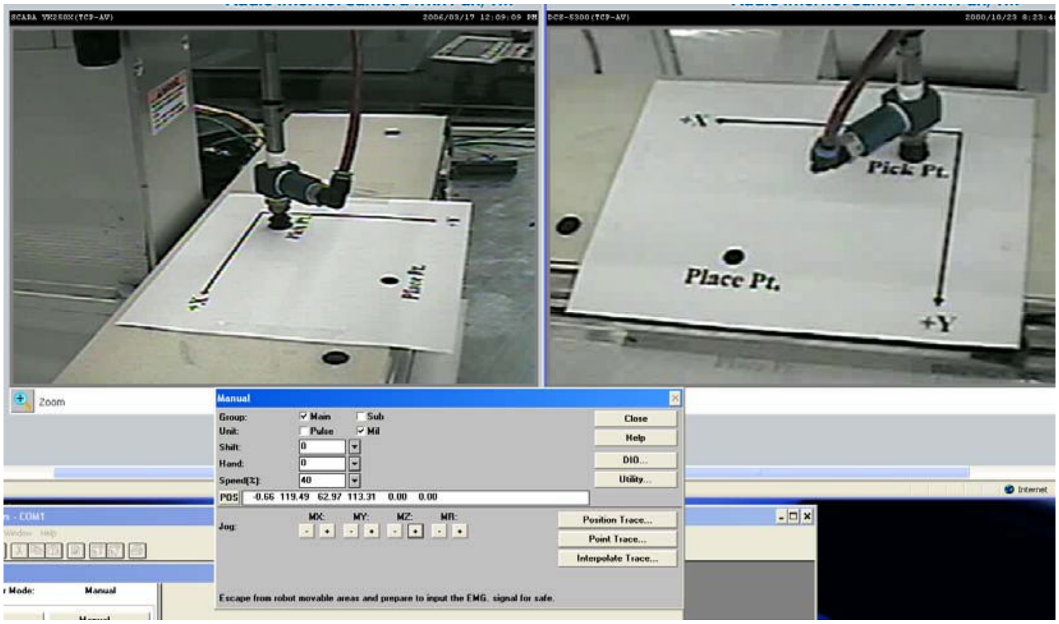

Figure 8. A snapshot of the viewing windows and the robot control panel.

A part of the compiled results from the first set is illustrated in Table 1. Each question was accompanied by a comment section, which is not fully shown in the table. For most students, the visual representation scheme seemed to appear adequate. Most found that the experiment was not difficult to perform and some even enjoyed the task. The students' comments point that more viewing windows, adjustable field of view, zoom-in features, and 3D effects would help their tasks, yet the additional visual feedback in representing remote systems do not appear to be very critical. Most used the two viewing windows simultaneously and if they used just one view, it caused the robot to miss the mark significantly. This phenomenon is typical to the errors associated with the lack of depth perception. Many indicated that having a third view (the top view) would help, however, more views would cause confusion or distraction. In order to verify the students' claims, the positioning accuracy was analyzed (Table 2). The analysis shows that the % error between the correct coordinates and the average of experiment data is quite small, indicating that students have performed well. For the question regarding the expenditure of mental effort as opposed to the direct viewing, about 60% of students felt that remote operations demanded a greater degree of concentration because the robot is viewed at an angle. Watching movements on the screen appeared to them somewhat unnatural, and the students would need to take some time and practice to get used to it. Also, many have agreed that having 3-dimensional views of the remote system would help the mental task, while leading to a less error.

The comments regarding the graphical information provide interesting insights towards the benefits of augmented information. The verbatim comments are indicated as follows:

1. This helped you better maneuver the robot and know exactly where to place the hands of it;
2. I would find the operation nearly impossible to achieve without these graphics;
3. I realize it was a simple experiment, more movement and turns would require more concentration and deliberate moves;

4. The x, y coordinate axes helped so you knew which axis to move the robot along to get to the points;
5. It helped me choose which button (e.g., +X or -X) to use to cut down my time.

In other words, any specific tasks such as driving a robot along predefined paths for assembly operations would require a high level of mental concentration due to several factors: (1) the difficulties in understanding of robot position with relation to the surroundings; (2) the small image size and the relatively confined field of view; (3) the cognitive fatigue in visualizing the 2D web images into 3D robot in terms of its orientation & direction of robot axes. This implies that in order for the online lab course to be more effective, the sensory feedback (audio/video feedback) to the remote users must be customized to suit the given tasks.

Table 1. The results of students' questionnaire from the first group (N=13)

Category	Question	Feedback
The remote system (SCARA robot) was represented by two display windows	How useful is this visual representation scheme to you in terms of operating the remote robot?	□ Very useful (31%) □ Useful (31%) □ Somewhat useful (31%)
	In order to operate the robot, I used two display windows simultaneously	□ Very often (23%) □ Often (46%)
	Would you prefer having more display windows (e.g., addition of top view)?	□ Strongly Agree (31%); □ Agree (23%); □ Neutral (23%); □ Disagree (15%)
	Would you prefer having an adjustable field of view (zoom-in & zoom-out features)?	□ Strongly Agree (23%) □ Agree (46%) □ Neutral (31%)
	Would you prefer having 3-dimensional views of remote system, instead of 2-dimensional display windows?	□ Strongly Agree (38%) □ Agree (31%)
	Do you think you performed well?	□ Strongly Agree (31%); □ Agree (38%) □ Neutral (23%)
	Remotely operating the robot required me a greater degree of concentration and expenditure of mental effort as opposed to the direct viewing:	□ Strongly Agree (15%) □ Agree (46%)
The remote system was augmented by additional information	How useful was the additional graphical information, while operating the robot remotely?	□ Very useful (46%) □ Useful (38%)
	What additional information do you wish to have that may help improve the operation of remote system?	Z-axis camera; Make the lens more focused, blurriness can cause eye fatigue; More cameras, and reduce lag between robot and video screen; Maybe have a Z-coordinate to illustrate Z+ and Z- for up and down; If we add help section that explain commands, which use command line to control the robot; I think the student can learn more easily by using the help (web), etc.

Table 3 represents the results from the second group. Most students found that the user interface is adequate and easier to use, as opposed to their already familiar teach pendant method. The computer based menus and buttons appear to them naturally, as if Windows-based graphical user interface. It also revealed that the time lag in the networks was the most frustrating factor to the students. Even though the students felt the experiment was not difficult, they preferred having an instructor present, in case of problems that might occur. It was interesting to note that, even after 8 weeks of familiarization, students still feel not confident about their knowledge on robot programming and commands. Therefore, they preferred having lab manuals or web-based instructional materials handy.

Table 2. Analysis of experiment data for positioning accuracy

	Pick Point			Place Point		
	X (mm)	Y (mm)	Z (mm)	X (mm)	Y (mm)	Z (mm)
Correct Coordinates	-1.00	117.58	63.00	80.41	201.53	63.00
Average of Experiment Data	-0.74	118.69	62.51	78.72	201.54	62.48
Standard Deviation	1.49	2.32	1.17	0.64	1.24	1.16
% Error	26.0	0.9	0.8	2.1	0.0	0.8

Table 3. The results of students' questionnaire from the second group (N=13)

Category	**Question**	**Feedback**
Delivery Technology: The robot was controlled by the commands sent over the web.	How easy was this operating scheme in comparison to the teach pendant method?	□ Very easy (54%) □ Easy (46%)
	Do you think the user interface for the remote operation was adequate?	□ Strongly Agree (15%) □ Agree (77%)
	What features did you like in the user interface?	Simple to use controls; multiple viewing angles
	What difficulties did you encounter while operating the robot remotely over the web?	Camera lag; delay; lack of depth perception; camera angle
	Do you think you performed well?	□ Strongly Agree (38%) □ Agree (54%)
	Would you prefer having an instructor present (in order to receive help), while remotely operating the robot?	□ Strongly Agree (61%) □ Agree (31%)
	Would you prefer having web-based instructional materials handy (such as robot manuals, description of the experiment, help menus, etc.), while remotely operating the robot?	□ Strongly Agree (46%) □ Agree (46%)
	Remotely operating the robot required me a greater degree of concentration and expenditure of mental effort as opposed to the teach pendant method:	□ Strongly Agree (15%) □ Agree (15%) □ Neutral (31%) □ Disagree (31%)
Instructional Technology: The robotic class was taught over the Internet.	I am already familiar with the programming of robot, hence I didn't need any manual or instructions	□ Neutral (23%) □ Disagree (61%)
	I have enough background knowledge of how to operate the robot efficiently. However, it was difficult to remember necessary commands in order to operate the robot.	□ Agree (38%) □ Neutral (31%) □ Strongly Disagree (15%)
	What additional information do you wish to have that may help improve the remote operation?	Manuals; examples
	Assume that you have to take this course online, and conduct all lab exercises over the Internet. Do you think you would learn equally well as in the classroom setting?	□ Agree (15%) □ Disagree (38%) □ Strongly Disagree (46%)
	If you have to take this course online, and conduct all lab exercises over the Internet, what suggestions would you like to make in order to improve the course instruction or labs?	Plenty of examples; clear step by step instructions; video instructions; improvements in GUI

Regarding the question about conducting the lab over the Internet, students feel that being in front of the robot and doing an experiment would likely teach them more. Students indicated that they need hands-on knowledge, lots of examples, clearly written step-by-step instructions, and plenty of online help, and that classroom lectures and descriptions always seem to help them learn more. Instead of taking the lab course online at home, students hope that the class will still meet so that they can ask questions, and preferred having the course offered in the computer lab with an instructor present. For the question regarding the expenditure of mental effort as opposed to the direct viewing, about 60% of students commented that it's about the same or even easier to do it online. This is contradicting to the first group, which used the teach pendant for robot control. The PC based control appear to them intuitively, and to be easier to manipulate the robot using a mouse. Except for the problems of delay and lack of depth perception, most found that a remote operation was an easy task.

VII. Conclusions

Overall, the online experiments provided interesting insights as to how to offer effective lab courses over the Internet. Even though the technologically advanced systems present seamless web accessibility, the specifics in tele-operations in line with the accompanying instructions multiply the complexity in creating a pedagogically effective online lab course. The absence of teachers, isolation of students, and the lack of detailed lab instructions, seem to present much more significant difficulties in online lab courses than the audio/visual modalities and the types of user interface.

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