International Journal of Industrial Engineering, 15(3), 323-329, 2008.

Web-Enabled Vision Guided Robotic Tracking within the Framework of E-Manufacturing

Yongjin (James) Kwon

Industrial and Information Systems Engineering
Ajou University
Suwon, South Korea, Zip 443-749

Corresponding author's e-mail: {Y Kwon; yk73@ajou.ac.kr}

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, but become 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 changing environment, which is better suited for today's rapidly changing environment. In this context, this paper presents an innovative method in part tracking using the Ethernet SmartImage Sensor and the web-controllable SCARA robot. Remote controlling of an automation process using Internet can suffer from time lag, if the network is congested with heavy data traffic, which maybe the greatest hurdle for using Internet for real time control. The approach discussed in this paper overcomes the time lag for part tracking and mathematically calculates the product locations on the conveyor at various instances and efficiently guide the robot to the product. The accuracy of the proposed scheme has been verified, which vindicates the industrial applicability of the setup. The web-enabled robotic operations present many benefits, such as ubiquitous access, remote control, programming, monitoring capabilities, and integration of production equipment into information networks for improved efficiency and quality.

Significance: The work presented in this study demonstrates the calibration of vision system with respect to the robot Cartesian coordinates; the tracking and speed calculation of parts on a conveyor; and the robot guidance for pick and place operations, all of which are conducted over the Internet. This signifies a novel approach in process automation, hence provides great potential for industrial application.

Keywords: remote operation of web-enabled robotic system s, vision guidance over the Internet.

(Received 15 April 2006; Accepted 20 April 2007)

1. INTRODUCTION

Industrial automation processes, primarily for pick-and-place operations involving robots, use various sensors for detecting the movement of product on a conveyor and guiding the robot to conduct subsequent operations. Such system requires precise calibration of sensors and tracking devices, usually resulting in a complex and time consuming setup. Furthermore, system agility to accommodate any product changes is based on the extent to which the system is reconfigurable and reprogrammable (Hsieh, 2003). Many previous works in the workcell design has addressed control and operations management issues such as scheduling, layout design, operation sequencing, and assembly plan design (Freedman & Malowany, 1988, Papanikolopoulos et al., 1993, Tay, 1996, Jiang et al., 1997). These research works address automation issues for a localized system. Recently, there has been a trend that conventional manufacturing systems (i.e., an island of automated equipment) are shifting towards information integrated systems, where a host of equipment becomes a part of the information network (e.g., Ethernet and Internet) for better access and control.

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'' (Koc et al., 2002, Lee, 2003). Other characteristics may include emergence, intelligence, non-deterministic, complexity, and self-organization in the enterprise system (Brezocnik et al., 2003). One of the enabling tools to realize the E-Manufacturing is the ability to predict the variations and performance loss (Lee, 2003). In tune with the trend, the authors at Drexel University have been developing web-enabled robotic systems. The constituents include highly advanced form of sensors and equipment, all of which identified by unique IP addresses. 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. Previous works in vision guided tracking involves lengthy derivation of complex mathematical relationships, which oftentimes susceptible to minor changes that frequently occur in production environment (Mattone et al., 2000, Motta et al., 2001, Bozma & Yal-cin, 2002, Gonzalez-Galvan et al., 2002, Gonzalez-Galvan et al., 2003). In today's manufacturing, where lots of changeovers are expected for a variety of part variations, such complexity is not suitable (Kwon et al., 2002).

2. EXPERIMENTAL SETUP

The experimental setup contains three pieces of industry equipment: a robot, a vision system, and a variable speed Dorner 6100 conveyor (see Figure 1). A DLink DCS-5300 web camera is used to transmit auditory and visual feedback over the Internet. 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 through its IP address and a port number. The Yamaha YK 250X SCARA (selective compliance assembly robot arm) robot can be controlled remotely through an onboard Ethernet card, which is 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, commands (e.g., speed, read and load program, turn motor on and off, move to points, etc.) can be sent to the controller to achieve desired results. The Telnet procedure has been included in the Visual Basic codes to develop an application program interface (API). The API improves the visualization of robot operation with an intuitive interface, which provides enhanced controllability for vision, web-camera, part identification and tracking, and robot functions. The connection between the API and the system was established by the utilization of Winsock components and various ActiveX controls that communicate through IP addresses.

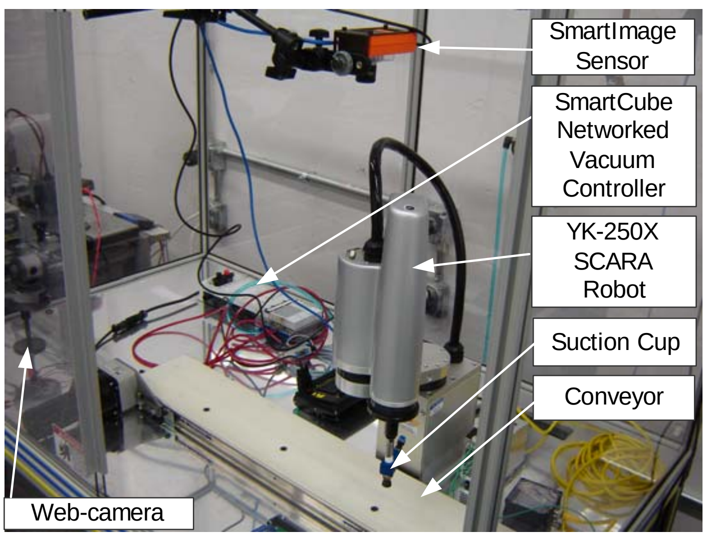

Figure 1: Experimental setup, showing the SmartImage vision sensor mounted directly over the robot

Another development with the API is that, it 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. Robot arm can be considered as a lower kinematic pair because the contact of two links occurs along a surface common to both links. The common surface of contact in this case is cylindrical and the contact pair is a revolute pair. Thus, two rigid bodies coupled by a revolute can rotate relative to each other about the axis of common cylinder. There are two links present in the SCARA robot. They are coupled with one another only at one end, hence the motion between them is relative. The first link is a manipulator base and the last link is an end-effector. The movement is in two dimensional planes (xy-plane), whereas the end effector moves in z-axis (vertical plane) and rotation axis (r-axis). The calculation for finding the position of the end-effector is basically focused on 2D plane where the rotational movement of arms exists. In SCARA robot arms, if a base link is displaced, the end-effector moves. The rotation movement of the link can be calculated using a transformation matrix:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \cdot \begin{bmatrix} x \\ y \end{bmatrix} \tag{1}$$

where x′ & y′ = transformed robot coordinates from original position denoted as x & y**.** Thus, first considering an angle α to be the rotation of first arm, one can calculate the coordinate transformation of its tip. Due to the displacement of the first arm, the second arm also gets displaced by the same amount with respect to the axes. The new coordinate of the tip of the second link becomes:

$$x_{New} = x_{Old} + (x' - x); y_{New} = y_{Old} + (y' - y) \quad (2)$$

If the second arm also rotates, then the above transformation matrix can be used to calculate its final position. The transformation for the second arm, which rotates by an angle β can be denoted as:

$$x = \cos\beta \cdot x_{New} - \sin\beta \cdot y_{New}; y = \sin\beta \cdot x_{New} + \cos\beta \cdot y_{New} \quad (3)$$

The method to analyze the robot manipulator is to use the reverse or inverse kinematics. If the initial and final positions of the end-effector are known, then the arm positions or rotation angle of the arms can be calculated. Inverse Kinematics is where Denavit-Hartenberg (DH) parameters come into use. The DH parameters for the SCARA robot would be in terms of a 2D coordinate system and there will not be any rotation with respect to z-axis (i.e., alpha = 0). The motion of a SCARA robot can be considered as a rigid body motion (invariant). That is, items do not change upon change of coordinate frame, although one can resort to a coordinate frame and vectors to compute distances and angles in order to represent vectors in that frame. The final result will be independent of the frame. Let's consider a coordinate frame, where A (x_1, y_1) represents the end-effector position, B (x_2, y_2) is the joint coordinate of two arms and the base of the robot is considered to be at origin O (0, 0). Let L_1 and L_2 be the arm length. For YK 250X, L_1 and L_2 are 125 mm (4.92 in.) and 125 mm (4.92 in.), respectively. When the position of the end-effector changes, its relative distance with respect to all other points remains the same. In this case, the distance between A and B is L_1 and between B and O is L_2:

$$L_1 = \left[(x_2 - x_1)^2 + (y_2 - y_1)^2\right]^{1/2}; L_2 = \left[x_2^{\,2} + y_2^{\,2}\right]^{1/2} \quad (4)$$

Solving these equations, the position of Point B can be found. Since the equations are quadratic, two values for Point B are obtained.

$$(x_2)_1 = \left[-B + (B^2 - 4AC)^{1/2}\right]\cdot\left[2A\right]^{-1}; (x_2)_2 = \left[-B - (B^2 - 4AC)^{1/2}\right]\cdot\left[2A\right]^{-1} \quad (5)$$

$$A = 4x_1^{\,2} + 4y_1^2; B = 4x_1(x_1^{\,2} + L_2^{\,2} + y_1^{\,2} - L_1^{\,2}); C = (x_1^{\,2} + L_2^{\,2} + y_1^{\,2} - L_1^{\,2})^2 - 4y_1^2 L_2^{\,2} \quad (6)$$

$$(y_2)_1 = \left[L_2^{\,2} - (x_2)_1^2\right]^{1/2}; (y_2)_2 = \left[L_2^{\,2} - (x_2)_2^2\right]^{1/2} \quad (7)$$

Two values of B result in two configurations of the robot arm. The optimized paths, which take the shortest time to travel, are built into the algorithms in the API.

3. SYSTEM CALIBRATION

The image captured by the camera and 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 2) can be mapped into the robot plane with the following functional relationship:

$$f : P(a_i, b_i) \rightarrow P(x_i, y_i) \quad (8)$$

By operating individual values of a_i and b_i by the scale factors S_x and S_y, the image coordinates (pixel coordinates) can be translated into the robot coordinates (mm in x and y directions):

$$P(x_i, y_i) = \begin{bmatrix} x_r \\ y_r \end{bmatrix} + \begin{bmatrix} S_x & 0 \\ 0 & S_y \end{bmatrix} \left\{ \begin{bmatrix} a_i \\ b_i \end{bmatrix} - \begin{bmatrix} a_0 \\ b_0 \end{bmatrix} \right\} + \varepsilon \quad (9)$$

where, *i = 1, 2…n,* $P(x_i, y_i)$ = translated robot coordinates (mm) from the pixel or image coordinates, ε = any errors associated with mapping, and x_r, y_r = a robot coordinate at the origin of the image plane ($P(a_0, b_0)$). Considering the work area as a 2D surface, the scale factors for each axis can be represented as:

$$S_x = \left[\frac{(x_1 - x_r)^2 + (y_1 - y_r)^2}{(a_1 - a_0)^2 + (b_1 - b_0)^2}\right]^{1/2}; S_y = \left[\frac{(x_2 - x_r)^2 + (y_2 - y_r)^2}{(a_2 - a_0)^2 + (b_2 - b_0)^2}\right]^{1/2} \quad (10)$$

The error due to lens distortion can be minimized 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 2 shows the division of the image captured by the camera into an *m* by *n* array. It shows that the images plane is not perfectly aligned with the robot coordinate axes, which is the case in most industrial applications.

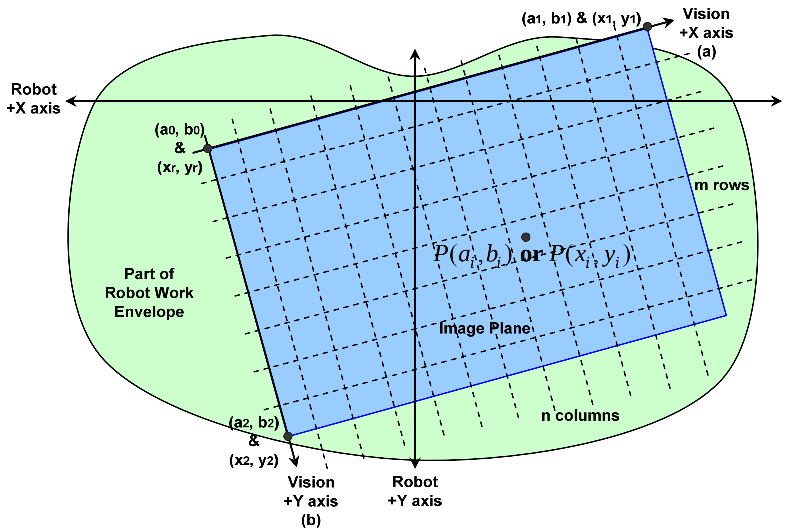

Figure 2: Coordinate system for machine vision (a, b) and SCARA robot (x, y)

The robot Cartesian coordinates at every intersection of the grid lines and the coordinate axes is stored and scale factors for each grid are calculated. Therefore, any point detected within the image plane will be scaled with respect to the increment in the grid from the origin. If $P(a_i, b_i)$ be any point detected, then $P(x_i, y_i)$ can be calculated as:

$$\begin{aligned} x_i &= x_r + \sum_{n=1}^{p-1} S_{x,n} \cdot \left| a_n - a_{n-1} \right| + S_{x,p} \left[a_i - a_{p-1} \right] + \varepsilon_x ; \\ y_i &= y_r + \sum_{m=1}^{q-1} S_{y,m} \cdot \left| b_m - b_{m-1} \right| + S_{y,q} \left[b_i - b_{q-1} \right] + \varepsilon_y \end{aligned} \tag{11}$$

where n = no. of columns, m = no. of rows, *p* & *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.

4. VISION TRACKING OVER THE INTERNET

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 (Figure 3). 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:

$$Speed(\Delta_p) = \left\| \mathbf{u} - \mathbf{v} \right\| \cdot t_f^{-1} = \left[(Ctr_{x,f} - Ctr_{x,f-1})^2 + (Ctr_{y,f} - Ctr_{y,f-1})^2 \right]^{1/2} \cdot t_f^{-1} \tag{12}$$

where $\mathbf{u} = (Ctr_{x,f}, Ctr_{y,f})$, representing x & y coordinates of the object center at frame no. *f*, $\mathbf{v} = (Ctr_{x,f-1}, Ctr_{y,f-1})$, representing x & y coordinates of the object center at frame no. *f-1*, and t_f= time taken for the part to travel from frame no. f-1 to frame no. f. The time (t_f) includes not only the part travel between consecutive image frames, but also the lapse for part detection, A/D conversion, image processing, mapping, and data transfer from the camera to a PC, which assumed to be equal for all images.

The delay in transfer of command data sent over the Internet occurs due to: (1) the route for transmission between two end points in a wide area is not fixed and (2) traffic congestion may be caused when too many users traverse the same route simultaneously (Yang et al., 2004). In a T1 line (which is used mostly in business sectors and universities LAN), data can be carried at a rate of 1.544 MBPS, which is many times faster than the residential network speed. Selecting a proper control structure promises a way to overcome the time delay problem (Yang et al., 2004). The process developed in this study effectively handles this as the detection and inspection are completed first, then the robot operation is done later without any requirement to stop the entire process. Thus, the available time between these two processes can be used to handle the uncertainties that may arise for Internet time lag. In addition, since the only data that the camera sends to the robot is coordinate points, tests showed that there were no delays in receiving the data over the Internet.

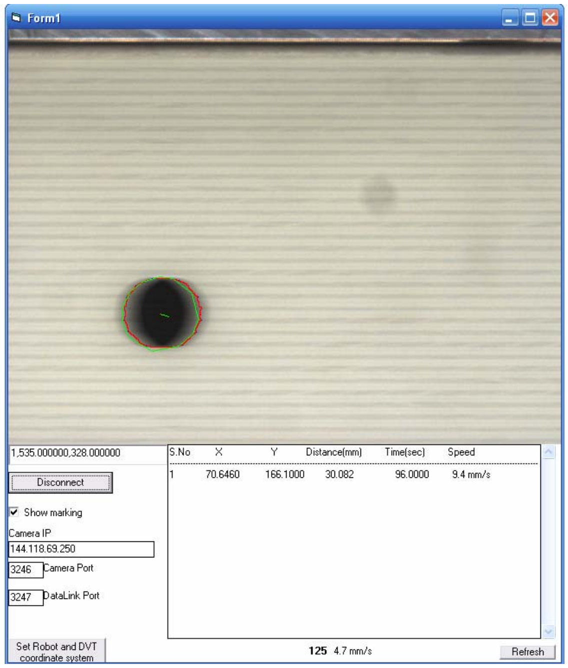

Figure 3: Snapshot of the subset of API for detecting part speed, image showing the moving object captured by the vision system.

The speed of the robot as provided by the manufacturer ranges from integer value 1 to 100 as a percentage of the maximum speed. The API calculates the speed of the moving objects, then coincides the robot speed. Once a part is detected, a future coordinate where the robot will reach and pick up the part, 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. The time taken for the robot to reach the part is set to be equal to the time taken by the part to reach that coordinate. The reach time t_r (ms) for the moving object and for the robot are identical and defined in the form of:

$$t_r = \left[\sum_{f=2}^{l} \left\| \mathbf{u} - \mathbf{v} \right\| \right] \cdot \left[\left\| \mathbf{u} - \mathbf{v} \right\| \cdot t_f^{\,-1} \right]^{-1} = \left[\left(x_i - x_0 \right)^2 + \left(y_i - y_0 \right)^2 \right]^{1/2} \cdot Speed_{Robot}^{-1} \qquad (13)$$

where f = frame number, indicating the first frame from which the vision system detects the center of moving object, l = frame number at pick up location, x_i & y_i = coordinate of the pick up location, x_0 & y_0 = the current robot coordinate. The vacuum suction cup attached at the end of the robot arm has a 20 mm diameter, and the object being tracked has 10mm diameter dots randomly placed on a conveyor. The experiments tested the accuracy of remote tracking as well as the pick and place operations over the Internet. The suction cup is able to lift the part, only if at least 50% of its area placed on the part. Under different speed settings (two different speed combinations of robot and moving object), the accuracy analysis of pick up operations was performed and the results are illustrated in Figure 4. The results show that the covered area is always higher than 50%, which is the required criterion for the end-effector to effectively lift the product.

5. DISCUSSION

The intense international and domestic market competition has driven the attention of manufacturers on automation of manufacturing systems as a means for increased productivity and quality. The advancement in web technologies allows the remotely located robots to be programmed, controlled, and tested. Robot and vision systems have been integrated in the network with individual IP addresses for easy access and control. Various image processing and analysis algorithms have been integrated with the API for remote vision tracking. These works have been tested over the Internet and found to be reliable and less susceptible to process changes. Operators can remotely adjust the inspection routine in the case of process changes, such as lighting conditions, part variations, and quality criteria. In the event of increased moving speed of conveyor, the part spacing (object separation distance) changes. The inspection speed and the inspection region should be adjusted accordingly. If the Intensity Sensor is used for detecting part contrasts from the background, the inspection variables such as threshold value, fill factor, min/max contrast, and min/max bright area can be updated through web access. The changes are necessary due to varying exposure time of passing parts on a conveyor and the time should be sufficient for the vision system to complete the intended quality control functions. This conforms to the changing environment to ensure the seamless transition between different production settings. One of the most problematic troubles associated with the vision system is the ambient lighting. Sometimes, a precise control of lighting is difficult and consequently, inspection routines may become ineffective. To counter such problem, the software functions, such as delay after trigger, exposure time, digitizing time, use of integrated illumination, use of anti-blooming filter, reflectance calibration, field of view balance, product sensor gain, and image area to acquire can be reset remotely. This capability provides less delay in production due to subtle or unexpected changes, which has a great potential, since engineers can access and control the equipment anytime, from anywhere.

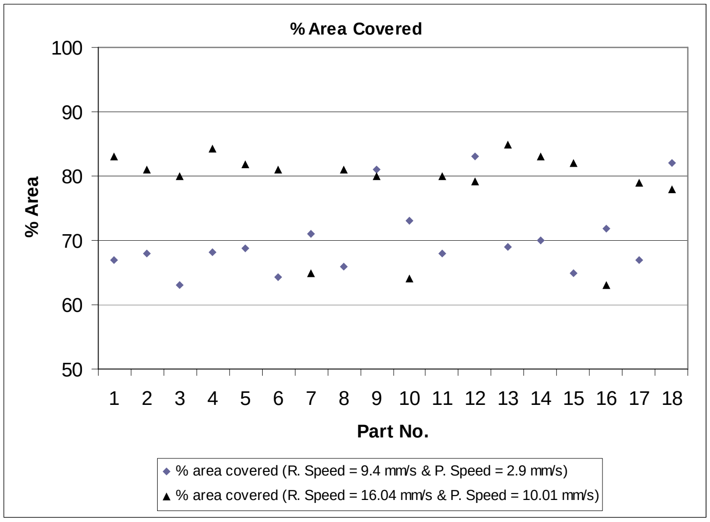

Figure 4: Plot for the % area covered by the robot suction cup

6. REFERENCES

1. Brezocnik, M., Balic, J. and Brezocnik, Z. (2003). Emergence of intelligence in next-generation manufacturing systems. Journal of Robotics and Computer-Integrated Manufacturing, 2003, 19(1-2); pp 55-63.
2. Emilio J. Gonzalez-Galvan, Sergio R. Cruz-Ramırez, Michael J. Seelinger and J. Jesus Cervantes-Sanchez, (2003). An efficient multi-camera, multi-target scheme for the three-dimensional control of robots using uncalibrated vision. Journal of Robotics and Computer Integrated Manufacturing, 2003, 19(5); pp 387-400.
3. Emilio J. Gonzalez-Galvana, Felipe Pazos-Floresa, Steven B. Skaarb and Antonio Cardenas-Galindo, (2002). Camera pan/tilt to eliminate the workspace-size/pixel-resolution tradeoff with camera–space manipulation. Journal of Robotics and Computer Integrated Manufacturing, 2002, 18(2); pp 95-104.
4. H. I-sil Bozma and H.ulya Yal-cin, (2002). Visual processing and classification of items on a moving conveyor: a selective perception approach. Journal of Robotics and Computer Integrated Manufacturing, 2002, 18(2); pp 125-133.
5. Jose Mauricio S.T. Motta, Guilherme C. de Carvalho and R.S. McMaster, (2001). Robot calibration using a 3D vision-based measurement system with a single camera. Journal of Robotics and Computer Integrated Manufacturing, 2001, 17(6); pp 487-497.
6. K. Jiang, L. D. Seneviratne and S. W. E. Earles, (1997). Assembly scheduling for an integrated two-robot workcell. Journal of Robotics and Computer-Integrated Manufacturing, 1997, 13(2); pp 131-143.
7. Koc, M., Ni, J. and Lee, J. (2002). Introduction of e-manufacturing. Proceedings of the International Conference on Frontiers on Design and Manufacturing, Dalian, China, July 2002.
8. Kwon, Y., Fischer, G. and Tseng, B. (2002). Fuzzy neuron adaptive modeling to predict surface roughness under process variations in CNC turning. Journal of Manufacturing Systems, 2002, 21(6); pp 440-450.
9. Lee, J. (2003). E-manufacturing—fundamental, tools, and transformation. Journal of Robotics and Computer-Integrated Manufacturing, 2003, 19(6); pp 501-507.
10. M. L. Tay, (1996). Optimizing robot workcell layout. Journal of Advanced Manufacturing Technology, 1996, 12(5); pp 377-385.
11. N. P. Papanikolopoulos, P. K. Khosla and T. Kanade, (1993). Visual tracking of a moving target by a camera mounted on a robot: A combination of Control and Vision. IEEE Transactions on Robotics and Automation, 1993, 9(1); pp 14-35.

12. P. Freedman and A. Malowany, (1988). Analysis and optimization of repetition within robot workcell sequencing problems. Proceedings of the 1988 IEEE International Conference on Robotics and Automation, Philadelphia, PA, USA, pp 1276-1281.
13. R. Mattone, G. Campagiorni and F. Galati, (2000). Sorting of items on a moving conveyor belt. Part 1: a technique for detecting and classifying objects. Journal of Robotics and Computer Integrated Manufacturing, 2000, 16; pp 73-80.
14. S. H. Yang, X. Zuo and L. Yang, (2004). Controlling an Internet-enabled arm robot in an open control laboratory. Assembly Automation, 2004, 24(3); pp 280-288.
15. S. J. Hsieh, (2003). Reconfiguration modules, programmable logic controller, and vision system for dual robot assembly workcell design. Journal of Advanced Manufacturing Systems, 2003, 2(2); pp 201-228.

BIOGRAPHICAL SKETCH

Dr. Yongjin Kwon has over 12 years of engineering experience in industrial and academic settings. He has extensive experience & practical knowledge in current design, manufacturing and quality control. His work has been cited a number of times in high profile journals. He was a faculty at Drexel University, located in Philadelphia, USA, where he developed Internet controllable robotics systems. He is currently a faculty at Ajou University, South Korea, focused on the development of web-enabled production systems.