A Highly Flexible, Automated, Parts Sorting and Transfer System

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ABSTRACT

In this work, a vision-based robotic system for the automated sorting and relocation of different parts has been developed. In the application under consideration, pre-defined but differently-shaped objects arrive on a moving conveyor belt in random order and in an unstructured manner. The objects are recognized and have their position and orientation measured by a vision sensor, and an industrial robot fitted with a highly versatile gripper picks up the objects from the moving conveyor and transfers them to different locations in a structured manner. The work demonstrates the development and integration of a number of different sub-systems to carry out an important industrial process in an automated and highly flexible manner.

1. INTRODUCTION

Consumer choice and discernment in today's richly supplied market have resulted in a shift towards the manufacture of products in smaller quantities and with an increased emphasis on variety. Although this state of affairs classically points towards more manual-dependent production, other factors may still mitigate towards a higher level of automation (see, e.g. [1]). In certain sectors, the pressures of competition may force manufacturers to continue to rely on a high level of automation to keep production costs down. In this regard, the new challenge that many manufacturing firms are facing is in the development of automated production systems that can be applied to different varieties of products, either through inherent flexibility or through reconfigurability.

A very common requirement of production systems is that of part handling, or more specifically, the requirement for an object to be transferred from one location to another. Indeed, most applications of automation in the discrete manufacturing industries, particularly where robots are involved, involve to a large extent the mechanization of parts handling, and failure to recognize the importance of meeting this requirement satisfactorily very often results in total failure of the entire automation project [2]. In most such applications of automation in industry, the general practice is to develop dedicated systems to ensure that the workparts maintain clearly pre-defined positions and orientations throughout the entire transportation process. While this approach certainly favours the attainment of reliability targets in automated production, it is generally lacking in flexibility. Application of the automated equipment to different workparts will normally require redesign, or at least reconfiguration, of the system. In particular, such a system is not suitable for an application where differently-shaped parts need to be handled during the same production run.

In this work, we have focused on developing a parts handling system that has a high degree of inherent versatility and flexibility, and that requires no reconfiguration for the handling of differently-shaped parts. The end objective is to be able to reproduce the performance of a human operator who recognizes different parts that arrive on a conveyor, irrespective of their exact position and orientation on the conveyor, and who is able to pick up the parts from the moving conveyor and place them in a number of predefined locations or bins in an ordered manner. The emphasis is on the ability of the system to recognize and handle a number of differently-shaped, predefined objects, which are being presented in random order, position, and orientation. A system of this nature will have applications in situations where differently-shaped parts are arriving in an unstructured manner, and where these parts must be sorted and prepared for a subsequent operation that requires structured parts presentation.

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Specifically, we have defined the general requirement of our prototype system, for demonstration purposes, to be as follows:

(i) At the input stage of the system, a human places a number of pre-defined but different objects on to a moving conveyor in random order, with only minimal restrictions on position and orientation.

(ii) At the output stage of the system, a robot picks up the objects from the moving conveyor, and places the objects, in a more structured manner, onto a number of different locations that have been pre-specified for the different objects.

2. Subsystem Selection And Development

2.1. Conveyor

The conveyor system for our application was designed and built in our laboratory, based on standard engineering guidelines and practice [3], [4]. Due to the relatively light weights of the range of the objects that would be transported (see section 2.3 below), it was decided to use a flat belt conveyor with an endless belt. For the prototype system the nominal belt speed was set at 3.5 m/min, and since motion was only required in one direction, motive power was required to only one of the two end pulleys of the conveyor. The conveyor is 1,500 mm long and 140 mm high, with a belt width of 300 mm. It is driven by a 90 W three-phase AC motor through a 50:1 reduction gearbox and has an angular speed of 30 rpm at the output shaft of the gearbox. The torque is transmitted to the driver pulley of the conveyor via a chain sprocket system.

2.2. Detection Systems

The sensing method that is normally a strong candidate for selection in applications involving the recognition of objects in an unstructured environment is that of machine vision (e.g. [5], [6], [7], [8]). In our application, due to the unstructured manner in which the parts were to be presented to the system, and due to the amount of object detail that it was envisaged would need to be detected, particularly in future extensions of the system capabilities, it was decided to utilize a vision-based sensing approach to recognize the objects and to determine the object positions and orientations.

Our choice of vision sensor lay between three general types – frame grabbers, PC-based vision systems, and smart cameras [9]. Frame grabbers are suitable for highly specialized applications, whereas PC-based vision systems allow for easier configuration of applications but still require significant time and expense during the development stage. Smart cameras are fitted with on-board processing that eliminates the signal conversion electronics, fixed frame rates, and gray-scale quantization typical of traditional machine vision systems, and allow dynamic access of the charged couple device (CCD). They represent the largest growth sector in the industry. Although somewhat less flexible than a PC-based vision system, a smart camera is more cost-effective and on this basis was selected for our project. The model used in our application is the DVT Smart Image Sensor Series 600, equipped with an 8 mm lens. This sensor has high resolution imaging capabilities (640×480 pixels) combined with network communications (Ethernet and fieldbus) making it a very convenient factory tool. The integration of DVT vision systems with industrial robots has already been demonstrated in applications using standard end effectors such as the palletizing of randomly presented paving slabs and in automotive assembly [10].

In our application the camera was mounted at a height of 550 mm above the conveyor, such that the longer side of the image was slightly longer than the width of the conveyor belt. Several experiments were carried out to determine the best lighting technique to be used with the camera, and it was found that in fact no special illumination was needed. The ambient light in the laboratory was found to be sufficient for the camera to acquire a very good image of the field of view. The exposure time was set at 20 ms and the sensor gain was set at 2.

The trigger for the camera was supplied by a BE300-DDT diffuse reflective photoelectric sensor from Autonics®. This type of sensor is able to detect transparent and translucent objects as well as opaque objects, and therefore adds to the flexibility of the system. The sensor has a range of over 300 mm, and was mounted on the side of the conveyor belt just upstream of the field of view of the camera.

A second, identical photoelectric sensor was mounted further along the conveyor just prior to the robot workspace, in order to provide the option of making accurate real-time calculations of actual conveyor speed, and in order to minimize timing errors, thus improving the reliability of the robot picking operation. This is discussed further in section 5 below.

2.3. ROBOT AND END EFFECTOR

The robot that was used in our application was a Unimate PUMA 260 industrial robot with a reach of 450 mm and a payload capacity of 1 kg. The robot was mounted at the side of the conveyor, about 500 mm downstream of the field of view of the vision sensor.

The end effector developed for our application is a versatile gripper that is able to conform to differently shaped objects [11]. This gripper has three fingers, each with three joints, and is equipped with a force sensing resistor (FSR) on each of its fingertips and with a photoelectric proximity sensor in its palm. It is driven by a single stepper motor that is located remotely from the device, and the drive from the motor is transmitted to the gripper fingers first through a flexible sheathed cable to the palm and then through a system of cables and pulleys to the fingers. The gripper control program is written in C and runs on a PC located close to the gripper. The interface between the PC and the actuator and sensors of the gripper is achieved via a standard data acquisition (DAQ) card with analogue and digital inputs and outputs. The gripper is able to grasp and pick up successfully a wide variety of different shapes and sizes of object, and applies grasping forces whose values can be pre-defined by the user. Due to payload limitations of the robot, the gripper in our prototype system can lift objects that weigh a maximum of about 0.4 kg. The gripper is shown in Figure 1.

A schematic plan view showing the various regions of interest of the conveyor is given in Figure 2.

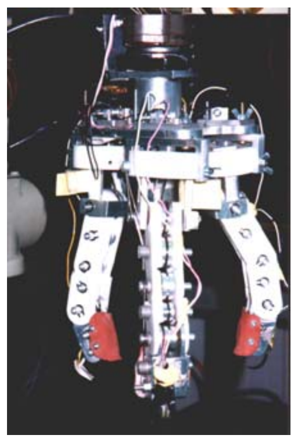

Figure 1: The versatile gripper developed for the parts transfer system

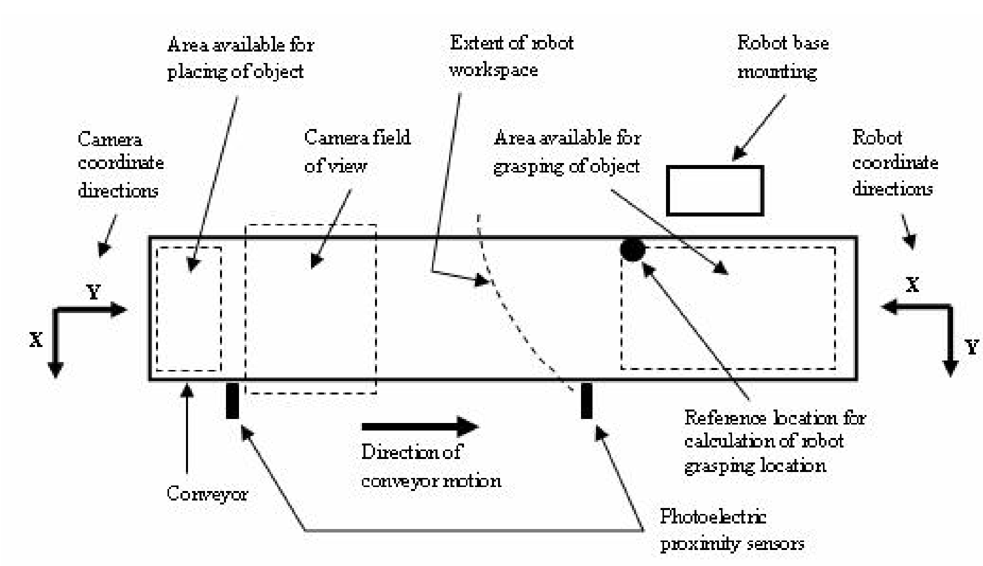

Figure 2: Schematic layout of conveyor (plan view)

3. IMAGE PROCESSING SYSTEM

The smart camera is equipped with an onboard processor that can run proprietary specialized image-processing routines installed as embedded software. User defined parameters and routines can be developed and programmed via a PC that runs proprietary software in a familiar operating system environment. The camera is also equipped with a breakout board which consists of power supply ports, and of twelve input / output lines that can be individually activated and are user definable.

The conceptual approach that was taken in this work was to first teach the camera, in offline mode, a number of different objects, defining specific parameters on the images such as the centroid positions. During system operation, the camera would take an image of each object passing beneath it on the conveyor, and analyze the image in real time using a suitable built-in routine. The camera recognizes the object and determines *(i)* the x-position of the object centroid within the camera coordinate system, converting the position value from pixels to mm, and *(ii)* the orientation of the object relative to the camera axes. The camera then outputs these data and the object identity as binary words through a number of the digital ports on the breakout board, communicating the required information to the robot through the input ports of the robot controller.

In our application, the field of view of the camera at the level of the conveyor surface was equal to an area of 365×270 mm^2 in real world coordinates, resulting in an image resolution of 0.32 mm^2 per pixel. Since the objects to be recognized were to be considerably larger than this scale, this resolution was considered sufficient. We used an 8-bit signal to communicate between the camera board and the robot controller, sending the x-position and object orientation data as two sequential words. Information on object identity was included in the first word. The nominal linear position resolution that was obtainable was of 1.18 mm, while the nominal angular position resolution was of 1.4^{o}. For the conversion from pixel values to real-world distances it was found that there were differences in the conversion factors needed for the central and edge portions of the conveyor belt, due to a non-constant distance between the camera lens and the surface of the conveyor. To circumvent this problem, three different sets of conversion factors were used depending on whether the object centroid was located in the region (0 to ⅓)w, (⅓ to ⅔)w, or (⅔ to 1)w, with w representing the width of the conveyor belt.

The inbuilt software of the DVT Smart Image sensor that was utilized in this application was the *ObjectFind SoftSensor*, set for "*light object on dark background*" (since the dark green conveyor belt registered as a dark colour in the images), and set in *auto bimodal* thresholding mode. Three objects were taught to the system for preliminary testing of the prototype. These were a standard floppy diskette box placed on the conveyor on one of its smaller faces (rectangular horizontal cross-section); a 0.5 L milk carton placed upright on the conveyor (square horizontal cross-section); and a cardboard cylindrical-shaped container of roughly the same height and volume as the milk carton placed upright on the conveyor (round horizontal cross-section).

4. GRIPPER CONTROL SYSTEM

The gripper control system is described in detail in [11], and was modified slightly to take into account the specific requirements of the present application. As described in section 2 above, overall control of the gripper is achieved through a program running on a PC, and via a DAQ card. When the program is run, the system waits for an input signal from an external device (in this case, as will be described below, from the second photoelectric sensor on the conveyor), and on receipt of this signal an output signal is sent to the stepper motor drive card to initiate the gripper closing sequence. Simultaneously, the program starts to sample the analogue inputs from the three force sensors on the fingertips. When the force registered by at least one of the force sensors reaches a predefined value, the motor is instructed to stop the closing motion of the fingers, and the PC sends an output signal to the robot controller to signify that the grasping process has been completed. The gripper control program then waits for a second input signal, this time from the robot controller, which signifies that the object has been transferred by the robot. At this point the PC sends an output signal to the stepper motor to start opening the fingers. When the gripper opening sequence is completed, the PC sends an output signal to the robot.

5. ROBOT PROGRAM

The robot is programmed to first carry out a number of initialization steps, and then the following sequence is executed:

(i) The robot moves to a convenient standby location above the grasping area.

(ii) The robot waits for a signal from the first photoelectric sensor on the conveyor, signifying that a new part is about to be processed.

(iii) On receiving this signal, following a preset delay, the robot reads the input signal from the camera, giving object identity and location of centroid along the width of the conveyor belt.

(iv) Following another preset delay, the robot reads the new input signal from the camera, giving object orientation with respect to the direction of belt motion.

(v) The robot moves to a location directly above the point where the grasping operation is intended to start, at the correct gripper orientation to optimize grasping, as determined by the information received from the camera.

(vi) The robot waits for a signal from the second photoelectric sensor on the conveyor, signifying that the part is about to enter the grasping area.

(vii) On receiving this signal, the robot program estimates the conveyor speed from the time delay between the two photoelectric sensor signals.

(viii) The program calculates the correct time delay required before the gripper descends over the object, based on the identity of the object, on its location along the width of the belt, on its orientation with respect to the direction of belt motion, and on the estimated belt speed.

(ix) Following this time delay, the gripper descends over the moving object, and starts to move horizontally along with the object in the direction of the moving conveyor. A signal is sent to the gripper controller to start the gripper closing sequence.

(x) The robot continues to track the object along the conveyor, while simultaneously waiting for a signal from the gripper controller that the object has been grasped.

(xi) On receiving this signal, the robot lifts the grasped object off the moving conveyor, and transfers it to the appropriate location.

(xii) A signal is sent to the gripper controller, to initiate the gripper opening sequence.

(xiii) The robot waits for a new signal from the gripper controller, signifying that the gripper opening sequence has been completed.

(xiv) On receiving this signal, the robot departs the object and moves back to the standby location, waiting for the next object.

The best orientation of the gripper relative to each of the objects, that would maximize the chances of a successful grasp, was determined offline. The durations of all the time delays in the above sequence, with the exception of that in step (viii), were determined offline during the development of the system, mainly from experimentation. In the case of the delay in step (viii), the optimum time duration was found to have a significant dependence on object location across the width of the belt, due to the shape of the profile of the sensing range of the photoelectric sensor. This is discussed further in section 7 below. The duration was also found to have a slight dependence on the orientation of the object, due to the fact that at different orientations the object triggered the photoelectric sensor at slightly different positions of the centroid along the belt. The duration was also slightly dependent on the object identity due to the different shape characteristics of the objects. In practice, it was found that the speed of the belt was sufficiently consistent to justify the omitting of the belt speed calculation in step (vii) of the above sequence, and of neglecting belt speed variations in the calculation of step (viii). For the objects under consideration, it was also found that the general cycle time could be reduced by starting the gripper closing sequence from the time of the second photoelectric sensor trigger, rather than from the signal described above in step (ix). This was because the finger movement between steps (vii) and (ix) would not be large enough to impede the motion of the gripper onto the object described in step (ix).

The robot program is written in VAL-II and consists of a main program for general control and two subroutines for the picking and placing operations.

6. OVERALL SYSTEM CONTROL AND INTERFACING

A schematic diagram of the communication lines in the overall control system is given in Figure 3. When the system is in operation, the three programs on the camera on-board processor, the robot controller, and the PC (for gripper control) run simultaneously. In summary, when a new object is placed on the moving conveyor, it will be detected first by photoelectric sensor no. 1. The signal from this sensor will trigger the image acquisition, image processing, and data output (to robot controller) routines of the camera, as well as the data input (from camera), and preparatory robot positioning routines on the robot controller. When the object is detected by photoelectric sensor no. 2, the signal will trigger the robot approach and tracking routines as well as the gripper closing sequence. When one of the fingertip force sensors on the gripper registers a pre-specified grasping force magnitude, this will stop the gripper closing sequence and trigger the relocation process by the robot. When the robot has completed the relocation process, the gripper opens and the robot is able to return to the standby location.

Appropriate signal conditioning circuits were developed to set the correct voltages and match impedances for effective communication between the different systems. Other circuits were built for opto-isolation between the main devices and the DAQ card, and between the camera and the robot controller. Where required, voltage regulators were used to set the input voltages to those required by the particular systems.

Figure 4 shows the complete system, with the robot gripper picking up a rectangular object.

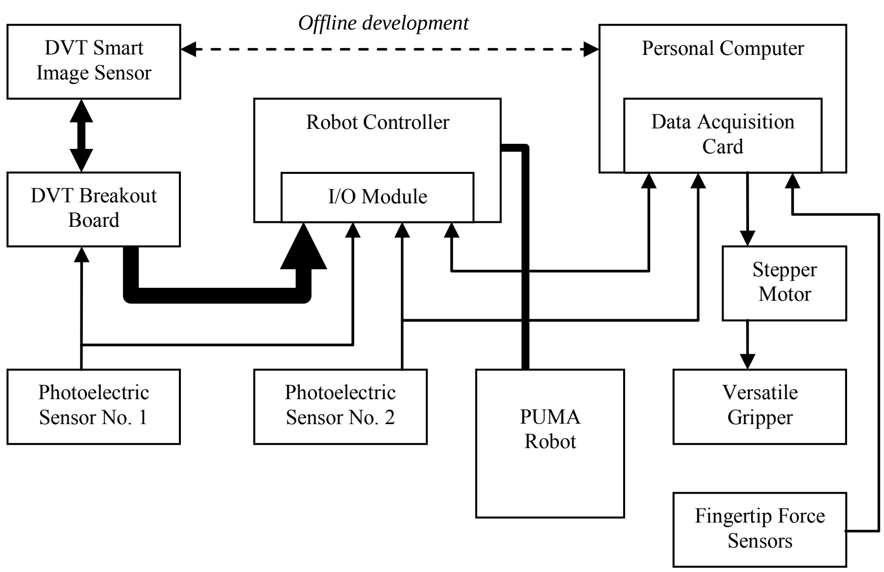

Figure 3: Overall control system

(a) Parts transfer system in operation

(b) Versatile gripper picking a rectangular shaped object

Figure 4: The parts transfer system

7. SYSTEM EVALUATION

A number of experiments were carried out to investigate the performance of the system. In the first experiment, the objective was to investigate the accuracy with which the robot could approach the centroid of an object passing through the system. An object of hollow cylindrical shape, of outside diameter 5 cm and height 7 cm was placed upright on the stationary conveyor and taught to the camera. The versatile gripper on the robot was replaced by a simple two-jaw gripper holding a pen, and a new program was written for the robot, requiring it to approach and mark the position of the object centroid on the belt. A sheet of paper was affixed to the surface of the conveyor, and the object was placed on the paper such that its centroid was at a known distance from the edge of the conveyor belt, as shown in Figure 5 *(a)*. The conveyor was then started, and the object passed through the system until it triggered the second photoelectric sensor, at which point it was manually removed from the conveyor. The position on the sheet of paper that was subsequently approached and marked by the robot (see Figure 5 *(b)*) was then recorded and compared to the actual position of the object centroid. The experiment was carried out for six different positions of the object across the width of the conveyor, with ten readings taken for each position. The average deviation from the required position approached by the robot across the width of the belt was of 4.6 mm, with a maximum error of 14.4 mm when the object was placed close to the edge of the belt.

In a second experiment the shape of the sensing range of the photoelectric sensor, in the horizontal plane, was measured by moving an object along the conveyor at different positions across the width of the belt, and noting the positions along the direction of belt motion at which the sensor was triggered. A plot of the sensor range is shown in Figure 6. The results of this experiment were used to set the robot delay before approaching each object, as a function of object position across the conveyor, as described in section 5 above.

A third experiment was carried out to investigate the performance of the photoelectric sensor that was located in the palm of the robot gripper, and this sensor was found to be significantly sensitive to the colour of the object. The sensor was therefore disabled in our system, and the robot was programmed to move down to a set height above the conveyor to grasp the objects. Effectively this set an upper limit, of about 15 cm, to the height of objects that could be handled by the system with the current settings.

A number of other limitations of the system, in the current configuration, were identified during testing. There is a lower limit of about 5 cm on the object height that can be handled, due to limitations in the vertical sensing range of the conveyor proximity sensors across some parts of the belt. There is also some variation in the sensitivity of the conveyor proximity sensors with respect to object colour – in particular the sensors are slower to respond if the object is transparent. Finally, there is a required time interval of at least 15 seconds between different objects to be processed by the present system, due to the robot and gripper cycle times.

(a) *(b)*

Figure 5: Measurement of centroid detection and robot positioning accuracy over the width of the conveyor: (a) position of object prior to image acquisition, (b) approach of robot towards object centroid position

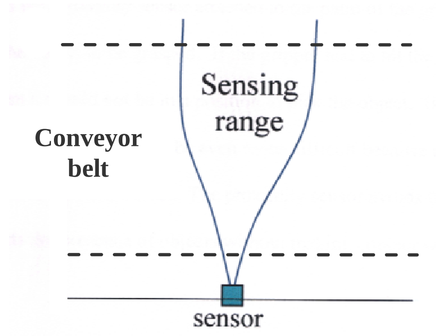

Figure 6: Sensing range of proximity sensors

8. Conclusion

A highly flexible, vision-based, automated parts sorting and transfer system has been developed. The system has applications in situations where different objects are being fed to the conveyor in random order and in a largely unstructured manner, and where these objects must be sorted and relocated or stored in an ordered manner. In the present work the system has been demonstrated for the sorting of objects that have a different shape, however in other applications the system can be applied to the sorting of objects according to colour or to barcode identification, or to the acceptance / rejection of objects based on inspection using machine vision. In particular this work has demonstrated the effective integration of different sub-systems: a smart camera, an industrial robot, a versatile gripper with force feedback, and a sensor-equipped conveyor, to carry out a fundamental industrial process.

Current work in this area is focusing on upgrading further the performance of the versatile gripper to increase its speed of operation in order to compare more favourably with manual handling times, on extending the range of objects that can be recognized by the camera and transferred by the robot, and on experimenting with different types of proximity sensor on the conveyor to increase system effectiveness and flexibility.

References

[1] *V. Lindström, M. Winroth, and J. Frohm, "Choosing Levels of Automation in Production Systems: Finding Critical and Supportive Factors", Proceedings of the EurOMA International Conference on Operations and Global Competitiveness, Budapest, Hungary, 2005.*

[2] *C. Ray Asfahl, "Robots and Manufacturing Automation", 2nd Edition, John Wiley and Sons, 1992, pp. 55-81.*

[3] *Ammeraal Process and Conveyor Belting, Design and Installation Guide, 1st Edition, 1995, p.4 (Ammeraal Beltech Holding B.V.)*

[4] *BS 490: Part 1: 1990, Conveyor and Elevator Belting, pp. 2-6; BS 4351: 1986, Portable and Mobile Troughed Belt Conveyors, pp. 5-8.*

[5] *P. F. Whelan and B. G. Batchelor, "Development of a Vision System for the Flexible Packing of Random Shapes", in Machine Vision Applications, Architectures, and Systems Integration, Proc. SPIE, Vol. 1823, pp 223-232, 1992.*

[6] *A. M. Howard, G. A. Bekey, "Prototype System for Automated Sorting and Removal of Bags of Hazardous Waste," Intelligent Robots and Computer Vision XV: Algorithms, Techniques, Active Vision and Materials Handling, Proc. SPIE 2904, pp. 271-277, Boston, MA. Nov. 1996.*

[7] *G. C. Causey and R. D. Quinn, "Design of a Flexible Parts Feeding System", Proceedings of the International Conference on Robotics and Automation, Albuquerque, NM, April 1997.*

[8] *F. Garcia, J Uusitalo, and R. Tuokko, "Robot Assisted Visual Quality Control in Mass-customized Production", Proceedings of the 37th International Symposium of Robotics (ISR 2006), Munich, Germany, May 2006.*

[9] *G. Collins and B. Silver, "Low-Cost Vision Sensors", Manufacturing Engineer, Vol. 80, Issue 2, April 2001 pp. 89-92.*

[10] *C. Connolly, "Vision Enabled Robotics", Industrial Robot: An International Journal, Vol. 32, No. 6, 2005, pp. 456-459.*

[11] *C. M. Seguna and M. A. Saliba, "The Mechanical and Control System Design of a Dexterous Robotic Gripper", International IEEE Conference on Electronics, Circuits, and Systems, Malta, September 2001.*