Real-Time External Control Coupled with Vision-Based Control for an Industrial Robotic Arm to Pick and Place Moving Object on a Conveyor Belt

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***Abstract*— This paper presents and implement a real-time external control software framework for a 6-DOF industrial robotic arm and object's orientation recognition coupled with a vision-based control system for the industrial robotic systems applications. The objects are moving on a conveyor belt. A computer vision system is designed to recognize the orientation of the object and to adjust the pose of the robot arm to a certain angle targeting the center of the object. The motion of the conveyor belt is synchronized with the Robot Arm, which is guided for grasping, moving and positioning objects in its position. The real-time external control and the adoption of computer vision technique for objects recognition are implemented using C++ and OpenCV library, and Windows Socket Library is used to establish a TCP/IP data exchange connection between the vision system on a PC and the robot controller. A GUI application has been developed to supervise the pick and place process. Experimental results show the effectiveness of the proposed scheme to achieve accurate positioning.**

***Index Term*— Real-Time External Control, Robot-Vision System, Industrial Robotic Arm, Industrial Robot Arm Applications.**

1 Introduction

In the resent years, Industrial Robotics has many extensive studies emerging the improvement and evolution of new technology. Sensor-based and visual feedback implementation enhances system control strategy. Thus, many researchers integrate vision systems with robotics systems.

Industrial robot arm integration in the industrial production systems is a fact. In some applications the industrial arm is the backbone of many assembly, pick and place and industrial manufacturing processes [1] [2] [3]. It also consider in many applications as a master for control of other machines connected in the automation lines [4] [5]. In modern factory automation, the robotic arm is greatly needed for control object grasping in well-developed way. This advantages increase with emerging computer vision techniques for object recognition not only in production pick and place process but also in welding applications [6] [7]. We can also use two cameras as a stereo vision system to estimate the depth of an object [8].

Sensory system usage improves the abilities for the industrial robotic applications to make the robot arm more intelligent and flexible. The industrial robot can see and recognize objects thanks to the new techniques of robot vision or machine vision technology. These vision techniques involve the theories and applications of computer vision, image processing, vision/robot calibration, and real-time communication [9] [10] [11]. Industrial robot can collect objects knowledge such as position, features, posture, dimension, and shape using good robot vision system to execute a manipulation process with a minimum cycle time.

Industrial Robots are, for so long, introduced as a superior automating solution in warehouses and at the end of many production lines in many industrial plants due to the high accuracy and short response time. However, the lack of flexibility of such solution with imprecise positioning of the product or changes in product's shape limits the reliability of palletizing Robots in industry [12]. Overcoming such problem with the addition of machine vision system guarantees efficient reprogramming of the robot and a tolerance with irregular forming of the products. On the other hand, it adds an obligatory delay due to the processing time of the captured scene [13], besides the essential need for industrial PC to handle the vision task with the conventional PLCs and robot controller, adds an inevitable delay for the intermediate communication [14]. These delays render the behavior of the system to match with Firm Real Time systems (FRT) [15], implying that missing a deadline may degrade the Quality of the Service (QOS) instead of enhancing the overall performance [16]. Some of the current research activities on autonomous picking and manipulation focus on object recognition and features extraction and design of special mechanical gripping system [17].

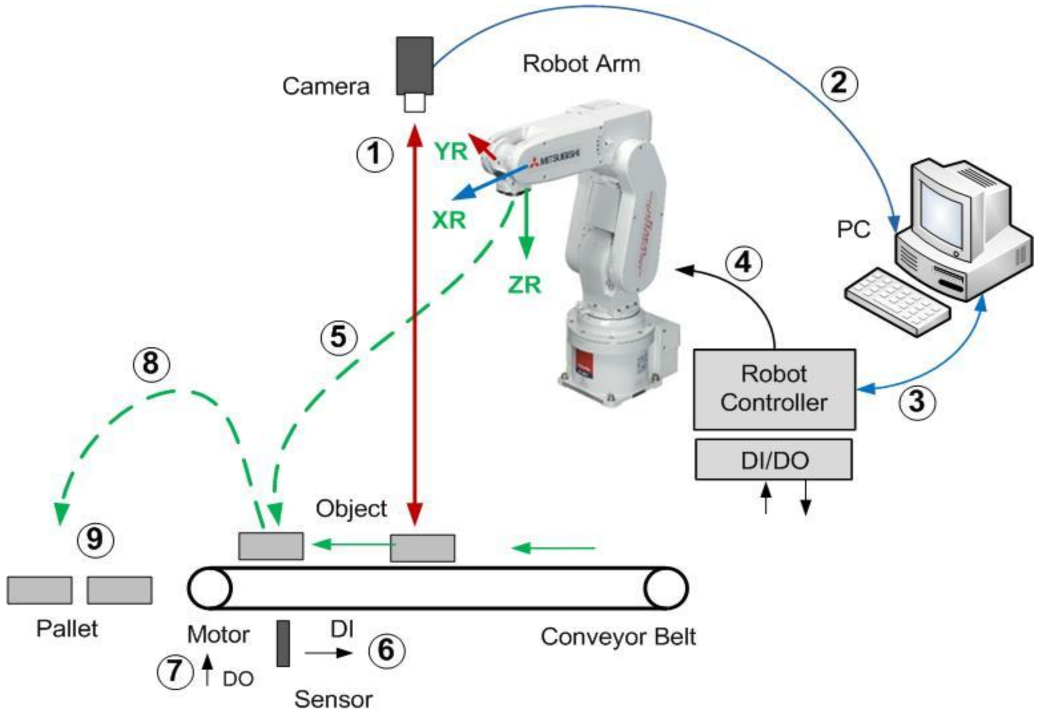

Fig. 1. System schematic diagram: (1) Camera that detects the object and sends video stream via (2) USB Link to a PC which processes the captured frame and extracts the coordinates to be send via TCP link to the robot controller and receives encoder readings from robot controller (3), and to Robot (4) a sensor is installed to detect presence of the object and(5) stop the conveyor motor (6), and let the Robot pick the object (7) then to follow (8) an arc path to (9) the pallet.

2 System Overview

This paper presents a real-time vision-based robotic system for tracking, orientation recognition and grasping for a moving object on a conveyor. This process could be used at assembly tasks, industrial manufacturing, palletizing and sorting. The used machine vision technique for object detection and orientation recognition is implemented by monocular 2D vision system using real-time external control running under C++ and OpenCV libraries.

For the grasping process in the industrial field, there are many types of robotic arm, such as articulated, SCARA, Cartesian/gantry robots, and dual-arm robots. All these different types are used not only at industrial field but at research approaches, as well. In this paper, the industrial robot Mitsubishi MELFA RV-2SDB, which is suited for the manipulation process, is used in the experimental work.

When applying a vision-based robotic system, it requires at least one camera as monocular vision system, or a pair of cameras as stereo vision system (stereoscopic) or a combination of many cameras. Also some sensors could be used for depth measurement such as laser distance measurement sensors.

Figure (1) shows the system design details as schematic diagram.

3 Monocular Vision System

For object detection and identification in a typical 2D vision system, a single camera can be used as monocular system. This vision system is commonly used in robotic systems applications, since image processing process is simple comparing to the others. But a 2D vision system cannot get the dimensions of the depth of scene. This makes a problem in detecting the pose of 3D objects.

The computer vision techniques used for object recognition could be recognition by the color of the object, by the feature/texture of the object, which is a pattern on the surface of the object, and by the shape.

3.1 Single Camera Model

Figure (2) show the pinhole camera model. Where ***C*** is called optical center and I is called image plane and ***W*** is the object point. The image plane ***I*** connect with the line that include optical center ***C*** and object point ***W*** at a point called image point ***M***. ***f*** is the focal length which known as the distance between optical center and image plane. The line that is orthogonal to image plane and passes through optical center is known as the optical axis. This optical axis connect with image plane at point known as the principal point.

If **w** and **m** is the coordinates of ***W*** and ***M*** respectively. A perspective projection matrix **P** which is 3×4 matrix show the relation between them as

$$m = \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \simeq \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \mathbf{Pw} \tag{1}$$

where $\simeq$ point to the equal up to scale. The perspective projection matrix **P** could be reformed into

$$\mathbf{P} = \mathbf{K}[\mathbf{R}|\mathbf{t}] \tag{2}$$

where [R|t] is known as camera extrinsic matrix and K is known as the camera intrinsic matrix and it is in the form of,

$$\boldsymbol{K} = \begin{bmatrix} \boldsymbol{\alpha_u} & \boldsymbol{\gamma} & \boldsymbol{u_0} \\ \mathbf{0} & \boldsymbol{\alpha_v} & \boldsymbol{v_0} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} \end{bmatrix} \tag{3}$$

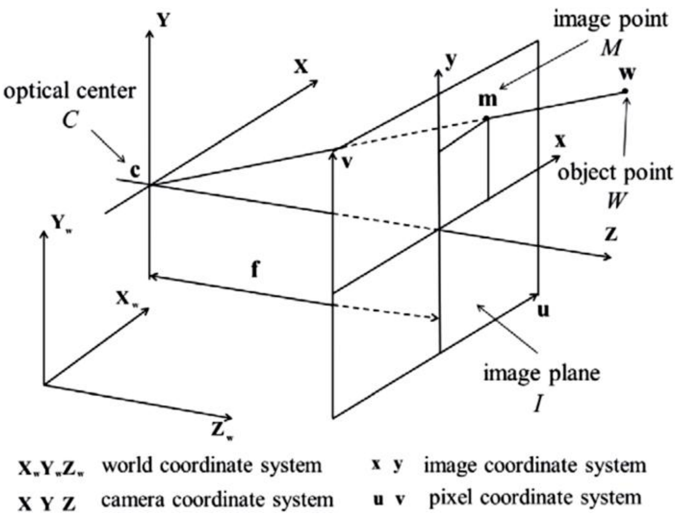

Fig. 2. Illustration of a pinhole camera model [18].

where $\alpha_u = s_u f$ is the focal length in $\boldsymbol{u}$ axis and $\alpha_v = s_v f$ is the focal length in $\boldsymbol{v}$ axis, $\boldsymbol{f}$ is the focal length of the camera in *mm* and s_u and s_v are the scale factors. (u_0,v_0) are the coordinates of the principal point, γ is the skew factor when u and v axes are not orthogonal.

To make it ease, we assumed that the horizontal and vertical focal lengths are the same and no skew exists between $\boldsymbol{u}$ and $\boldsymbol{v}$ axes. So, we can get

$$\boldsymbol{K} = \begin{bmatrix} \boldsymbol{\alpha} & \mathbf{0} & \frac{w}{2} \\ \mathbf{0} & \boldsymbol{\alpha} & \frac{h}{2} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} \end{bmatrix} \tag{4}$$

where $\boldsymbol{w}$ is the width of the image and $\boldsymbol{h}$ is the height of the image. The camera extrinsic matrix is 3×4 matrix containing camera's position and orientation. It contain a rotation matrix $\boldsymbol{R}$ which is 3×3 matrix and a displacement vector $\boldsymbol{t}$ which is 3×1 vector. The focal plane is the plane that is parallel to image plane and include $\boldsymbol{C}$.

As stated by [19] [18], the Cartesian coordinates $\tilde{c}$ of C is given by

$$\tilde{\boldsymbol{c}} = \boldsymbol{R}^{-1}\boldsymbol{t} \tag{5}$$

Then, any optical beam that goes through M and C can be denoted by the set of points **w**, where $\boldsymbol{\alpha}$ is a constant.

$$\tilde{\boldsymbol{w}} = \tilde{\boldsymbol{c}} + \boldsymbol{\alpha}\boldsymbol{R}^{-1}\boldsymbol{K}^{-1}\boldsymbol{m} \tag{6}$$

3.2 Vision System Calibration

There are different types of coordinates. The coordinates that describe the relation between the object and the main (X, Y, Z) coordination are known as world coordinate. For the camera, the coordinates that describe the relation between a point and camera coordinates are known as camera coordinates. Also, there are image coordinates which are the two dimensional coordinates of a point on the image plane.

There are two types of calibration: camera calibration and robot/camera calibration [9]. For the robot/camera calibration, it make a connection between the coordination of the camera and the coordination of the robot. But for camera calibration, it is very important to make a calibration for the cameras for all vision systems such as monocular vision system, stereo vision system and multi-camera vision system [20] [21] [22]. We make this calibration to correct some parameters. Because usually camera comes with internal defect due to the manufacturing such as lens distortion, lens misalignment and the alignment of two cameras in stereo camera [23].

These parameters are Extrinsic Parameters and Intrinsic Parameters. The parameters that link the coordinates of the camera to the world coordinates and identify its position and orientation in space. It is denoted as Extrinsic Parameters or Exterior Projective Parameters. Other parameters that link the coordinates of the camera to the perfect image coordinates in which image coordinates have their origin at the principal point is denoted as Intrinsic Parameters or Interior Projective Parameters. The intrinsic parameters are the effective focal length, the image center, the scale factor, the radial distortion coefficients and the tangential distortion coefficients [24].

3.3 Object Detection and Orientation Recognition

In order to mitigate the effect of the delay introduced by the processing time of the image processing code, we implemented fast algorithms based on combining a primary stage of color filtering and a secondary stage of edge detection and area filtering on a video stream as in the flowchart shown in figure (3) taking advantage of the fixed lighting condition assumed in any industrial plants.

We applied *cvtColor* function found in OpenCV library that converts an image from one color space to another in order to convert the frames to a gray scale then filter them based on color. Then, for the rectangle detection algorithm a function called *canny* function using the algorithm introduced in [25] is applied to detect the rectangle by detecting the edges.

For the sake of calibration, the coordinates of the object extracted from the captured frames are referred to the robot world coordinates; hence to increase the flexibility of the robot we applied time estimation function and dynamic picking point (PP) estimation to predict the instance at which the object reaches the coverage area of the robot and to indicate the place, within this area, where the object will be located.

The X and Y coordinate of the PP of the object is calculated as follows.

$$\boldsymbol{PP} = \begin{cases} \boldsymbol{x}' = \frac{\boldsymbol{h}}{2} * \mathbf{sin}(\boldsymbol{\theta}) \\ \boldsymbol{y}' = (\boldsymbol{O}'\boldsymbol{y} - \boldsymbol{O}\boldsymbol{y}) + \frac{\boldsymbol{h}}{2} * \mathbf{cos}(\boldsymbol{\theta}) \end{cases} \quad (7)$$

Where h is the hypotenuse of the object in cm and θ is the angle of the object. $O'y, Oy$ are the y coordinates of the camera frame origin and robot origin relative to a reference.

Time Estimation function is:

$$\boldsymbol{t} = \frac{\frac{\boldsymbol{l}}{\boldsymbol{l}'} * \boldsymbol{x} - \boldsymbol{x}' + \boldsymbol{d}}{\boldsymbol{v}} \quad (8)$$

Where t is the estimated time to reach the end of the conveyor and l, l' are the length of the object in cm and pixels respectively. d is the distance between the origin of the camera and the origin of the robot world coordinates and v is the speed of the conveyor in cm/sec.

The pixel to cm ratio is calculated by dividing the actual length of the object in cm by the measured length in pixels. The ratio is then multiplied by the current distance of the object from the origin of the camera frame to get the distance in cm. The distance between the origin of the camera frame and the origin of the robot is added to the previous distance. Finally, we add the effect of the rotation angle of the object to the total distance. The total distance is then divided by the speed of the conveyor to estimate the time to reach the origin of the robot.

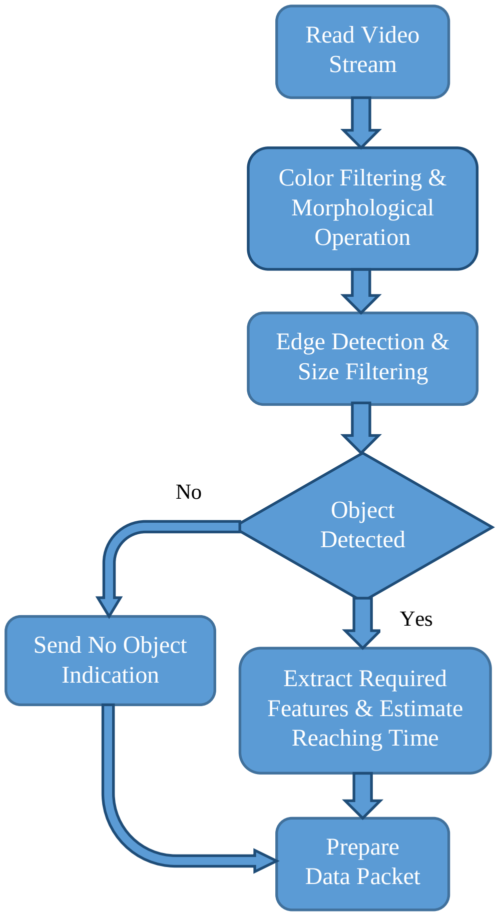

Fig. 3. Computer Vision Algorithm: The frames are converted to gray scale then filtered based on color, then applying morphological operation to reduce the noise. Rectangle detection algorithm based on edge detection using canny function is then applied on the processed frames.

4 REAL-TIME EXTERNAL CONTROL SOFTWARE FRAMEWORK

In networked applications, selecting the appropriate communication protocol is very important. The most common protocols used in robotics applications are User Datagram Protocol (UDP) and Transmission Control Protocol (TCP). We choose and use the suitable protocol according to the sort of the data.

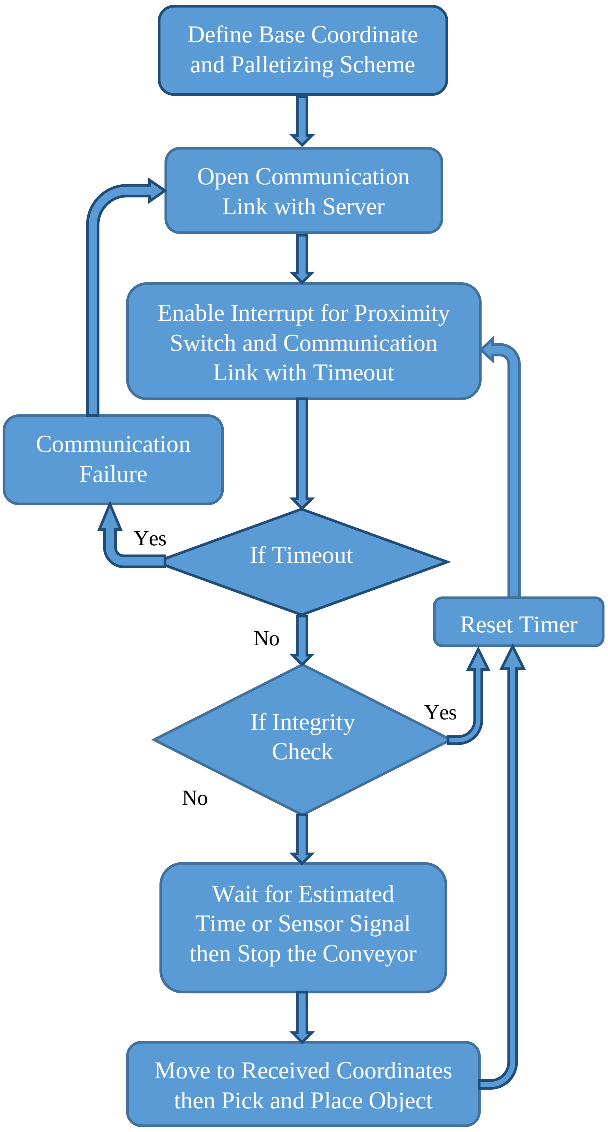

Fig. 4. Motion Control Task Flowchart.

We use TCP in the case of sending high-level commands such as picking an object or changing robot's pose. Sending commands using this kind make it certain to perform the tasks. TCP is used in these tasks owing to its reliability. TCP protocol presents retransmissions once packets get lost or corrupted [25].

On the other hand, UDP is used in the case of sending low-level commands. These commands are used for low-level control robot motion that request different network requirements. In low-level commands, a higher bandwidth is needed and reliability isn't a serious issue. This protocol applied for these cases because packets are diminished and delays decreased. If there are some packets are missing, the robot will keep on moving as long as the packet is still be transmitted [25].

For the data communication for the sake of building a protocol that handle the data between the robot and the PC, we set the type of the application layer to be producer consumer with an integrity check each 10 seconds to assure data integrity between the PC and the robot on the channel. This technique gives the privilege of avoiding successive overhead delays when opening TCP channel between the client and server, and assuring the readiness of the channel whenever useful data are available [26].

The integrity check routine is interrupted whenever an object is detected, leaving a room for useful data packet to be transferred to the robot controller. The data packet consists of: the time estimated to pick the object, the roller angle of the robot and the estimated PP of the object as described in figure (4). The consequences of packet loss are cumulative lags in the robot action. These consequences are bypassed by periodic clearing of the socket buffer, and the re-establishing of the network on a new port to avoid sneaking of old data packets to the robot controller.

The vision system technique is directly coupled with the developed real-time external control framework of the industrial robot to perform the right grasping process of the object. The installed hardwired sensor stops the conveyor whenever the proximity sensor is interrupted, as a backup and protection, thus it maintains the required performance of the process.

5 EXPERIMENTAL VERIFICATION AND VALIDATION

In this paper we present the design and implementation of pick and place process of moving objects on a conveyor belt, making use of vision system to recognize the object and its orientation, and also to adjust the pose of the robot arm to a certain angle targeting the center of the object, then controlling a Robot arm via data exchange for grasping, moving and locating objects in its position. The motion of the conveyor belt is synchronized with the robot arm based on an estimate of object location, and an additional proximity position sensor is used as backup to stop the conveyor belt.

Figure (5) depicts the experimental setup. The Mitsubishi Robot controller is connected via Ethernet cable to a PC. A low resolution USB camera of 640*480 pixels' frame is fixed to a conveyor at 60 cm and connected to the PC. Robot controller is connected to 32 I/O digital module, a single output point is connected to the conveyor motor through a 24 V relay, a single input point is connected to a photo proximity sensor. The gripping technique is via a suction cup connected to a vacuum ejector and a pneumatic valve. We make the robot place the objects in a pallet form and the pallet position is installed at the end of the conveyor. The pallet pattern is predefined by the user and fed to the GUI interface, while the robot controller's main function is to execute the motion control algorithm and to perform robot's joints control. The vacuum gripping system is controlled through on-off control of the compressor, according to the pressure level, and the pneumatic valve control whenever the suction cup is placed on the center of the object with the correct angle.

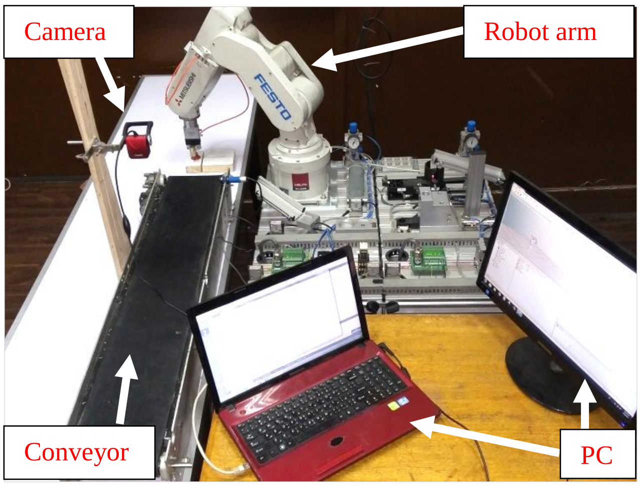

Fig. 5. Experimental setup.

5.1 GUI

Graphical User Interface (GUI) is widely used in many applications [27]; because it offer a simple and ease way for operating and monitoring. A GUI has been developed using a multiple-threads approach. It was achievable by having 3 threads running in our application. The construction of our application is shown in figure (6) from the point of view of threads.

Figure (7) shows the GUI in action. Three main labels (QLabel objects) were used to show the original video stream and the 2 other image processed streams: Original, Canny output, Gray scale output streams. Another 3 labels were used to show the name of each stream. Five buttons are used: Start and Stop Communication - Start and Stop Vision - Edit Parameters. Clear and Quit buttons are included. Three Status indicators are included: Communication - Vision - Palletizing.

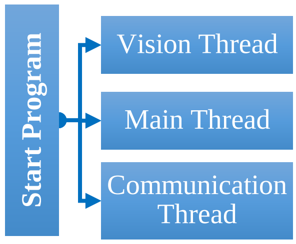

Fig. 6. Application structure from the point of view of threads.

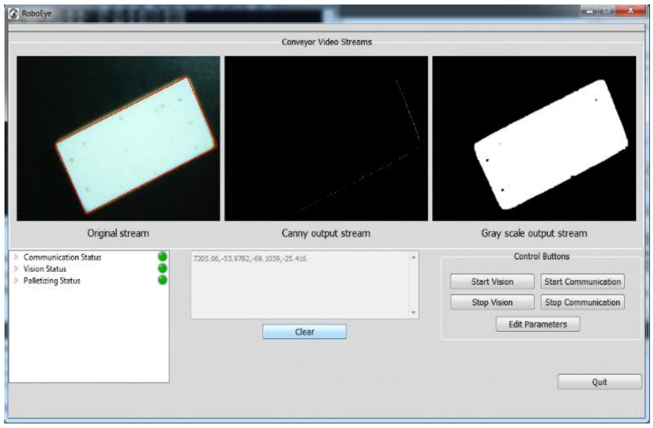

Fig. 7. GUI Application.

5.2 Results

To verify and validate this work, we use this work in a palletizing application. We use an object in a rectangular shape which could represent a packaged product in a box. The pattern of the pallet is shown in figure (8). The fast detection algorithm used in vision was able to detect the object even at high speed movement of the object inside the camera frame. The total time of frame processing and transmission of data packet is between 90 to 100 *msec*. Each sample is equivalent to about 0.33 *sec*. The total time of acquisition of one object is about 9 seconds at 60% of the Robot full speed while processing time is below 100 *msec*. and here we are restricted to image processing concept which is time consuming. The rectangular object is detected as shown in figure (9). Pictures depicted in figure 10 (a, b, c), illustrate the robot while picking and placing the object.

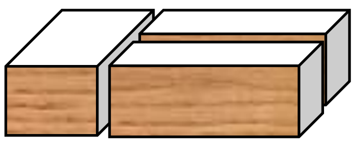

Fig. 8. the pattern of the pallet.

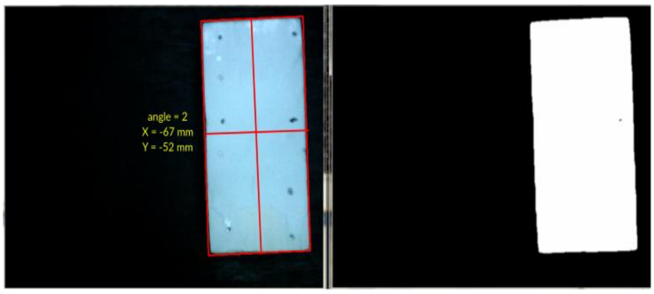

Fig. 9. Image processing results showing the angle and the X-Y coordinates of the object and the processed & filtered frame to the right.

6 CONCLUSION

The proposed vision system is integrated with the real-time external control algorithm framework of the robotic arm Mitsubishi MELFA RV-2SDB based on C++ software. This way is possible for object detection and object orientation recognition moving on a conveyor, with no earlier knowledge of the pose and the orientation.

In this paper we successfully managed to ride through some major disadvantages of automating palletizing of moving objects using vision based palletizing Robot. Time and dynamic picking point estimation are techniques introduced as a solution to the inflexibility and sensitivity of palletizing Robots to minor changes in products' shape and irregular formation. An innovative technique is implemented that includes the use of industrial Robot arm, simple machine vision using low cost camera and standard networking algorithms to prove integrity and portability of such solution in industry with high reliability. A GUI has been developed using a multiple-threads approach. It was achievable by having 3 threads running in our application.

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(a) (b) (c)

Fig. 10. (a) Robot while picking where the reference angle of the vacuum ejector is aligned with the object angle, (b) Robot path while picking the object and (c) Palletizing stage of the object forming the predefined pallet pattern.

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