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An automated supermarket checkout system utilizing a SCARA robot: preliminary prototype development

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Abstract

In recent years, a number of retail stores have introduced self-checkout systems at the cash point, however these normally require a high degree of participation by the customer, often leading to requests for help by store attendees. A review of the literature has shown that the use of robots at checkout points, with their potential to reduce customer effort, has not yet been addressed. A separate literature review has shown that the four-axis SCARA robot, used extensively in the manufacturing industry due to its advantages in cost, speed and rigidity, is rarely applied to service tasks. In this work these two research gaps are being addressed. A first prototype of an automated supermarket checkout system, exploiting the advantages of the SCARA robot and including machine vision, has been developed. The system is able to recognize various items placed by the customer on a conveyor, transfer the items to a container, pack them neatly, and total the bill. Evaluation of the prototype indicates that acceptable speed and reliability of the system can be attained.

Keywords: Service robot; supermarket; machine vision

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1. Introduction

The introduction of robots and other forms of automation in retail stores has gained popularity in recent years, as they not only improve the customer's shopping experience but also draw people into the store, allowing the stores to remain competitive with online stores [1]. The goal of all shopping robots is to make shopping in retail stores easier. Typical functions include providing product information, finding products and transporting the selected items [2]–[5]. For instance, LoweBot, a NAVii autonomous retail service robot, aims to help customers find their required products, allowing store personnel to focus on other tasks [6]. The robot can also detect any gaps or patterns that may affect business decisions by scanning inventory and capturing real-time data. Another example is the Intelligent Shopping Assistance System, ISAS [7]. ISAS has two modes of autonomous functions which avoid the need for the customers to push the cart with the selected items, thus allowing the customer to focus on what s/he needs to buy.

One of the tasks in a retail store that can potentially be carried out using a robot is the checkout process. Technologies such as self-checkout systems already exist and allow the customer to scan his/her items, bag and pay for them without any assistance from store personnel [8]. By installing self-checkout systems, the retail store employees' time can be used more efficiently to improve customer service. The use of the self-checkout system can also be a good experience for the customer, since it provides the user with more privacy. Additionally, the time spent waiting in queues at the checkout point could be reduced since the checkout process is faster and more efficient. A potential disadvantage of self-checkout systems is that the customer may make a mistake when scanning an item that causes the system to stop and alert one of the shop's personnel to solve the problem; which could be embarrassing to the customer [8]. Thus, by automating the checkout process further by using a robot, this problem would be addressed. A number of innovative ideas have been proposed to automate the identification of products in a checkout system (e.g. [9], [10]), however no evidence was found that a fully automated checkout systems exists.

Two standard robot configurations that would be able to automate the checkout process of a retail store are the revolute robot and the Selective Compliance Assembly Robot Arm (SCARA). The revolute robot has six degrees of freedom (DOF), and is able to access its 3D workspace with arbitrary gripper orientation. The SCARA robot is a jointed two link arm, with three revolute joints that allow it to manoeuvre in the horizontal plane and a prismatic joint that moves vertically. Hence, with only 4 axes, the robot can only orient an object about the z-axis. Despite this restriction, a SCARA robot has been selected for this study due to its efficiency, precision, speed, rigidity, very good reach over wide area for objects that can be gripped from above, and lower cost (e.g. [11]).

The SCARA robot is used extensively in the manufacturing industry for processes such as object transfer and assembly insertion. It has also been used in other industries such as the food industry [12], education [13] and laboratories [14], however in general the use of the SCARA robot in the service sector is minimal.

The objective of this paper is to explore the feasibility of developing an automated retail store checkout system using a SCARA robot. In this study the type of retail store considered is a supermarket, due to the widespread presence and use of these stores. The identified application is under development and a preliminary prototype has been built and demonstrated. The standard design cycle: problem analysis; conceptual design; embodiment design; detailed design; and evaluation, was utilized to develop the robotic system.

The robot utilized in this work is the Epson SCARA robot model E2S651S available in our laboratory. It is a standard tabletop model, with a rated payload capacity of 2 kg, including the end effector of the robot.

2. Preliminary problem analysis and general specifications

The checkout process of a supermarket consists of three major steps; scanning, bagging and paying. Therefore, in an automated checkout process, the three steps involved would need to be automated without human intervention. For the automated checkout system to be successful, it would need to at least match the performance of existing systems in the market and also be easy to use, without imposing too much constraints on the customer, so as to encourage him/her to make use of the system without worrying about making a mistake.

Additionally, the system must be able to handle various products of different shape, size, weight and even packaging. For this project, a small set of typical but varied supermarket products were considered, namely a deformable flour packet, a 1 L milk carton, a can of tuna, a small spice jar, a toothpaste tube, a medium-sized cereal box, a packet of popcorn and a deodorant can. The maximum payload capacity and motion range of the robot were considered when selecting the mentioned items. Therefore, the maximum weight to be carried was limited to 1 kg, i.e. the weight of the 1 L milk carton.

A versatile end effector would be required, to enable secure grasping of selected items, without damaging them. Additionally, the time taken to grasp and release the product should be minimal to further increase the performance of the process. The constraints of the robot should also be considered during the design of the end effector.

To increase the probability of success of the system in the market, it is important to understand the requirements and features that are desired by the supermarket owners and also by their customers for the automated checkout system. Hence, "the voice of the customer" of the automated checkout system was captured through structured questionnaire surveys which were directed to the owners of three major supermarkets and to 34 customers from different demographics. From the surveys it resulted that the customers were open to the idea of an automated checkout system as long as it is safe, reliable, easy to use and fast. Meanwhile, the most important additional aspect for supermarket owners was ease of maintenance.

Based on the surveys, the Quality Function Deployment (QFD) and the Product Design Specifications (PDS) were constructed for both the robotic system and the end effector. From the QFD of the robotic system it was observed that the most important issue to be addressed during the design process was efficiency. Meanwhile, from the QFD of the end effector which was based on requirements identified in the problem analysis, the most important aspect of the end effector was speed. Other important aspects from the two QFDs included safety, cost, versatility, and in the case of the end effector, low weight.

3. Conceptual design stage

3.1. Solution synthesis of the robotic system

Structured design methods were used to help brainstorm ideas to develop the most effective solution. A function means tree was utilized, where the main functions of the problem were identified, to understand better the problem. For each function, a number of means were attached, and the tree was then used to generate alternative solutions for the robotic system. The most effective solution was then chosen using a decision matrix which ranks the concepts based on the technical requirements listed in the QFD.

A schematic layout of the system is shown in Fig. 1. In this concept, the customer interacts with the system via a screen and a button to initiate the process. The button triggers the robot to index the item within the field of view (FOV) of a smart camera. Once the products are within the FOV, the system captures an image of all the products present and analyzes it. From a unique barcode attached at approximately the centroid of the product, the camera can determine the number of products present, their identities, as well as their locations and orientations. Thus, the customer can place the products in random positions on the conveyor belt as long as the barcode is not occluded. This information is then sent to the robot. In the meantime the products are indexed so that they are within the reach of the robot, from where the robot can grasp the products with the designed end effector and place them in a container. A box was chosen to serve as a container in this early study, due to its rigid structure which makes it easier for the robot to keep a record of where the products are placed so that other products can be placed in suitable positions. The items which were not detected are taken to the rejects area via a small ramp from where the customer can pick them and pass them through the system once again. In the meantime, the camera is triggered so that it can start analysing the next set of products. The process is continued until the customer presses the button again.

In this concept, the robot and the machine vision operate simultaneously, reducing the cycle time of the process, while allowing sufficient time for the customer to place the products on the conveyor belt. Additionally, it interacts with the customer via simple means and if the customer does not follow the instructions, the system will still operate without any trouble due to the rejected objects area.

3.2. Solution synthesis of the end effector

An end effector allows the robot to interact with the environment. In literature, there are different types of end effectors able to grasp various objects, varying from mechanical grippers with two or three fingers [15], suction grippers [16] and magnetic grippers [17], to jamming grippers [18]. For the end effector, a function means tree was

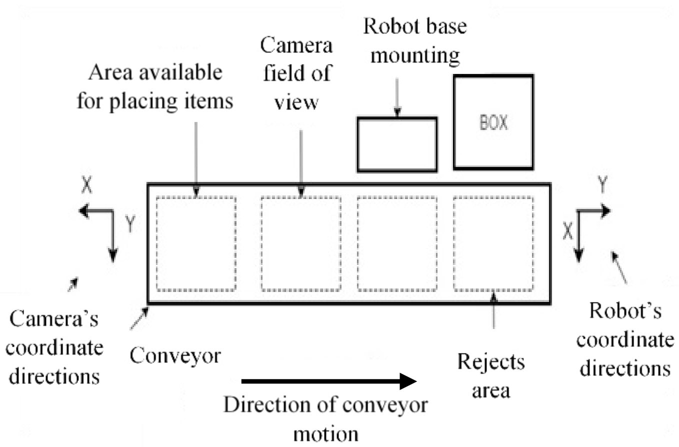


Fig. 1. Schematic layout of the concept.

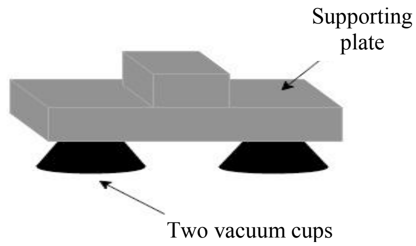


Fig. 2. Conceptual design selected for the end effector.

once again constructed, to understand better how the selected products could be grasped. Various concepts were generated for the end effector and the most suitable conceptual solution was chosen using a decision matrix, based on their ability to satisfy the technical requirements listed in the QFD of the end effector.

The conceptual solution that was finally chosen (Fig. 2) consists of two fixed vacuum cups, in order to be able to hold products with non-rigid packaging and/or items that are relatively heavy, with a more stable grasp. Smaller and lighter products can be grasped using only one vacuum cup. This also allows the possibility for two products to be grasped at the same time, hence reducing the time the robot needs to travel. This end effector requires only one surface to grasp the products. Thus, there are no restrictions on the distance between the products to be grasped.

4. Embodiment design of the robotic system

4.1. Design of the end effector

In order to lift the maximum weight of 1 kg using two vacuum cups, within the size constraints of the target object set, and using appropriate safety factors, it was determined that two cups of size 32 mm diameter operating with a vacuum pressure of 63.4 kPa would be adequate. The type of cups used were silicon bellows 1.5 Fold, which facilitated the grasping of surfaces that were not completely horizontal or were curved.

For this application, the venturi vacuum generator was opted for since the vacuum pressure required, is relatively low and it is relatively cheaper, lasts longer and has faster response times when compared to a vacuum pump. However, air leakage was expected for certain products that did not have a rigid structure or that are porous. Hence, from an experiment carried out the leakage volume was determined so that a suitable venturi vacuum generator could be chosen.

A venturi vacuum generator was assigned to each vacuum cup, as shown in Fig. 3, so that the vacuum pressure does not drop in the vacuum cup, risking dropping the products if adsorption errors occur. Each venturi vacuum generator was also connected to a solenoid 3/2 way valve so that the robot is able to switch on each ejector independently, as required.

After the functional design of the end effector, a material selection exercise was carried out to determine the material from which the end effector structure should be manufactured. The design requirements, such as the need for the end effector to be as lightweight as possible, while still be stiff to avoid oscillation when moving, and to possess high strength to withstand the load, were considered when selecting the most suitable material. The material that was finally chosen was AL-6061 T6 since it has medium to high strength and good corrosion resistance, toughness and machinability at a reasonable price [19].

4.2. Design of the machine vision system

The smart camera that was used was a Cognex 535c vision sensor, which is a standalone imaging sensor, and which was already available in our laboratory. The vision sensor works with Cognex Intellect Software which allows the user to program the camera for inspection, using a number of programmable tools available.

The objective of the machine vision system was to determine the number of products present in the FOV of the camera, and to identify the products and their locations from the unique barcode attached to the items. The smart camera utilizes the blob counting tool to determine the approximate location of the barcode, thus determining the location of the product's centroid and also its orientation. The 1D barcode reader software then reads the barcode. The system then compares this barcode with those in its database to determine the unique Product_ID.

The number of products together with their Product_IDs, their locations and orientations are sent to the robot using Socket Objects for Transmission Control Protocol/Internet Protocol (TCP/IP) communication over an Ethernet connection. The sockets can send out byte variables corresponding to the American Standard Code for Information Interchange (ASCII) value of the characters in the information to be sent. However, the socket is only able to send one byte at a time. Thus, the robot interprets the series of bytes received and where necessary, a number of consecutive bytes are grouped together to represent one piece of information. The robot then returns the character corresponding to the numeric ASCII value.

The information that the vision system concludes from the analysis is highly dependent on the image quality. Thus, the quality of the image must be optimized by selecting the most appropriate lighting system, since although pre-processing operations can be done to improve image quality this would increase processing time. A number of illumination systems were considered: ambient light, ring light, integrated lighting and spot light. However, there was no obvious solution, thus further tests were conducted as summarized in section 5.

4.3. Design of the material transfer system

A flat belt conveyor with an endless belt driven by an AC motor, also already available in our laboratory, was used to index the products from one stage of the process to the next. For indexing purposes, the conveyor requires an external trigger, in this case, this was done by the robot. Once the robot triggers the conveyor to move, it needs to wait a certain amount of time before turning it off, so that the products on the conveyor belt move the necessary distance. The optimal time delay was determined empirically and was found to be 3.96s.

However, the pickup location of a product will depend on where the customer places the product along the conveyor belt in the first instance, and the product also must remain stationary while it is being indexed. A number of different solutions were considered and the concept that was chosen was to mark a number of consecutive squares on the conveyor belt to indicate the allowable areas where the customer could place the items. In each area, a series of parallel protruding strips (ridges) where attached at equal intervals to restrict rolling of objects.

4.4. Overall control and interfacing

When the automated checkout system is in operation, the smart camera, the robot controller and the conveyor need to operate together so that the system can achieve its objectives. The controller of the robot ensures that the external devices operate as intended through the use of a program which bases its decisions on the information received from the external devices. A schematic diagram of the communication lines in the system is given in Fig. 4.

When the automated checkout system is turned on, the system displays a message box informing the customer on how to use the system. The customer is instructed to place the products on the conveyor within the markings, with the barcode facing up. The robot will then wait for the customer to initiate the process by pressing a button.

Once the customer presses the button, the robot indexes the conveyor and then triggers the camera. When the machine vision system has analyzed the captured image, it sends all the necessary information to the robot which is waiting to receive the data. The robot then indexes the products and triggers the camera once again to determine the next set of products.

In the meantime, if the machine vision system has detected and identified any products present in the FOV, the robot moves the end effector to grasp the products, taking into consideration the known height of the products so as

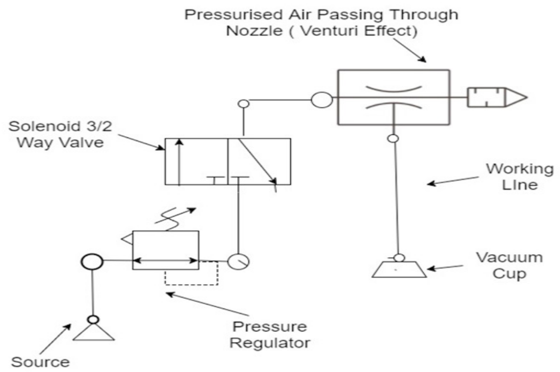


Fig. 3. Pneumatic system to create vacuum, normally closed.

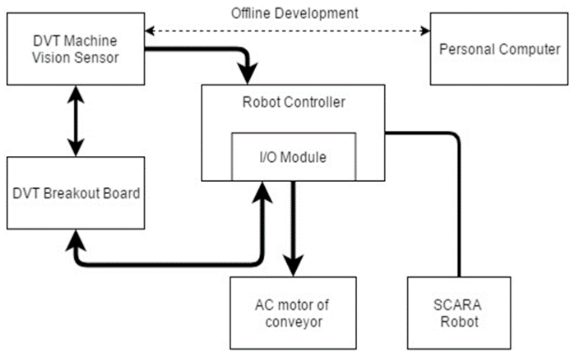


Fig. 4. Overall control system.

not to the damage the other products that might be present. From the Product_ID, the robot knows the number of vacuum cups required to lift each product, its name and its price. Hence, if only one vacuum cup is required the robot adjusts the end effector so that one of the vacuum cups aligns with the product, and then grasps other products that might be present which also require one vacuum cup.

4.5. Packaging algorithm

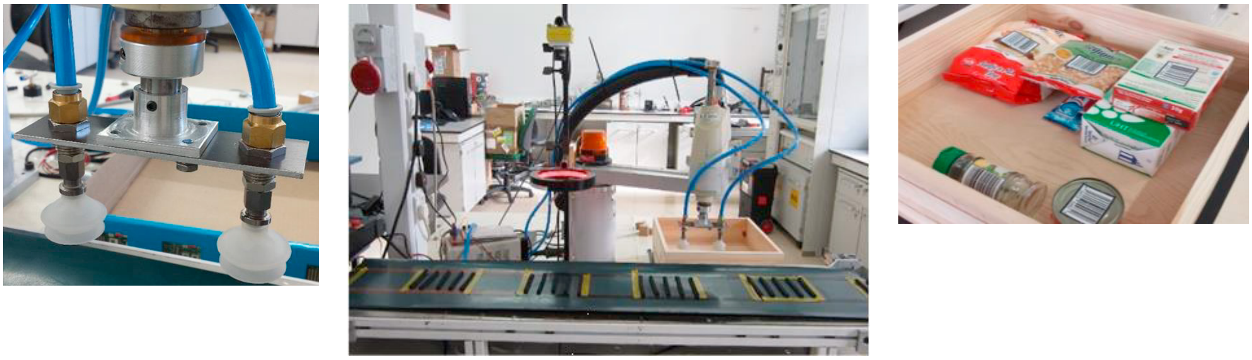
Once products are grasped, the robot must find positions in the box where to place the items. An algorithm was developed to pack the products in a strategic way taking into consideration the space available in the box and the geometric parameters of the grasped product, such as its shape and dimensions. The algorithm also takes into account the products already present in the box and their geometric parameters. When placing the products in the box, the program takes into account how the end effector will approach the box without hitting any of the sides or the products already present in the box, so that none of the products are damaged in the process. The other products that might be present in the FOV are grasped in the same way. The same process is repeated for the next set of products, unless the box is full, at which point the robot will inform the customer and will wait for him/her to replace the current box with an empty box, before continuing to execute the program. When the customer presses the same button again, the robot will end the transaction and display the total price for the packed products. The robot will then wait for the next customer to initiate the process once again.

5. Detailed design and implementation of the robotic system

The final step of the process is the detailed design, where the design is refined even further to ensure that the overall solution has satisfied its objectives. Most of the parts used for the end effector were standard components, except for the mounting and supporting plate of the end effector. Detailed drawings of the custom components were drawn up so that they could be manufactured out of AL-6061 using CNC milling. All the parts were then assembled as shown in Fig. 5(a) and the pneumatic tubes were mounted in such a way so as not to interfere with the movement of the robot.

The smart camera was then mounted onto a stand, whose height could be varied manually. The most suitable working distance was determined, by varying the distance between the camera lens and the conveyor and each time focusing the camera on barcodes of different dimension. The optimal working distance was chosen based on the size of the FOV of the camera and the barcode sizes. The type of barcode that was chosen was EAN-8 with a magnification of 150 %, since it is smaller compared to the EAN-13 with the same magnification. The barcodes were generated using Barcode Studio 15.4, and were printed and attached to the products.

Once the smart camera was set up the different illumination systems mentioned in section 4.2 were tested to determine the most effective one. From the tests carried out, the low angle lighting with variable brightness was chosen, as it provided a constant and uniform lighting across the FOV of the camera.



(a) (b) (c)

Fig. 5. (a) the end effector; (b) the complete automated checkout system, developed as per the schematic shown in Fig. 1; (c) products packed into a box by the robot.

When the working distance of the machine vision system was determined, the size of the FOV of the camera was known. Hence, a number of squares of the same size as the FOV (117x155 mm) were marked on the conveyor, at equal intervals. The squares were not directly adjacent to each other to allow some space for the end effector to move freely when grasping the products. Five strips were also placed at equal intervals in each square to restrict cylindrical products from rolling while being indexed. The developed system is shown in Fig. 5(b).

6. Evaluation of the robotic system

Once all the sub-systems of the automated checkout system were implemented, a number of tests were carried out to evaluate the system with respect to the QFD and the PDS.

The objective of the first test was to evaluate the performance of the machine vision system. Different scenarios were considered: no products present in the FOV; each product placed in a different position within the FOV; and more than one product present in the FOV. Most of the time the system was able to detect correctly the presence of an object and send the robot the correct information, even when only part of the product was visible, as long as the entire barcode was in the FOV. On average, the machine vision sensor took about 5.59 seconds to process the data. It was observed that the vision sensor takes less time to detect the presence of the products and to send the information when there is more than one product in the FOV. Hence, a smart camera with a higher resolution would improve the performance of the system as the customer would be able to place more items in the FOV of the camera. Also, the conveyor would not need to be indexed as often. During this test, it was observed that the communication used between the robot and the smart camera was still not robust enough. Since the robot does not have any prior knowledge of the information each byte is carrying, it could occasionally misinterpret the data. The communication between the smart camera and the robot can be improved by using protocols such as Modbus TCP.

For the second experiment the performance of the end effector was tested by grasping the various products and transferring them to predefined positions using the robot. All the selected products could be grasped securely. Successful grasps were also achieved for other products of different shapes and sizes including paper-thin products.

Another test was carried out to investigate the time taken for the system to pack the items, and the accuracy with which products were handled and packed. The automated checkout system was run as designed and the scenarios that were considered were: one product at a time; two products at a time; and four consecutive products at a time. It was observed that all the products were easily grasped and placed it the box as shown in Fig. 5(c). On average, the overall time, from when the button was pressed until the product was placed in the box for a single product was 19.99sec. When four different products were processed after each other, the average overall time was 62.85sec, which is less than if the individual times of the products were to be added, since now the smart camera and the robot are operating simultaneously. However, the time per product is still rather long when compared to a traditional checkout system. The main contributing factor to this was the conveyor, as the product spent a total of almost 8sec on the conveyor, during which time the other devices were idle. Moreover, in the present system, the use of an AC drive for the conveyor sometimes results in loss of synchronicity with the camera FOV. Thus, a timing belt conveyor powered by a stepper motor can be implemented for better speed control. Another important aspect is cost, as this determines the economic feasibility of investing in such a system. When compared to a traditional supermarket paying the cashier at minimum wage, it was calculated that break-even can be achieved in less than a year. Additionally, if the process time is improved, it would be able to replace more than one cashier.

7. Conclusion and future work

An Epson SCARA robot was used successfully to demonstrate automation of the checkout process of a supermarket. The system was able to identify a number of different products of different shapes and sizes, and place them systematically inside a box, which the customer can then take home. The performance of the system can be improved by using a machine vision system with higher resolution, by using a timing-belt conveyor, and by improving the communication between the camera and the robot, as discussed in section 6.

Safety and Security are two measures that should also be considered in an automated checkout process. Safety is crucial when dealing with robots, especially service robots, where the sole purpose is to work with humans who may not have much knowledge about robots. Thus, a risk assessment needs to be carried out, where the automated checkout system is analyzed so as to identify any potential hazards and their potential consequences. Security measures can also be introduced, to avoid shoplifting, by using techniques such as weighing scales to cross-check product weight information during checkout.

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