Automated pneumatic vacuum suction robotic arm with computer vision

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Abstract. In this paper, a 4 DOF robotic arm that made of acrylic was built and equipped with a 5 MP USB camera, a pneumatic vacuum suction cup and a small air pump. An image will be captured by the camera and then processed with computer vision algorithms. The algorithm will extract the coordinate from the object image. The extracted coordinate data from test objects then fed to the microcontroller. Pulses were generated by the microcontroller to the driver module to control the motors. Some parameters were changed and adjusted accordingly to achieve a different result for analysis purpose. Objects that are used in this research are boxes with various shapes, colors, surface sizes, and weight. The result, the robot was able to reach the object within 2 mm to 4 mm tolerance. Image processing algorithm centroid calculation errors are within 2 mm. Vacuum pickup success rate is 99%.

1. Introduction

Due to the competition of the global markets and the need for fast adaptation of production to the ever-changing market request, which can be met only by radical advances in current manufacturing technology, thus, a huge development and improvisation have made in recent years at around the globe to achieve the concept of industrial 4.0 which targeted to achieve high-efficiency workflow and qualitative process yet doesn’t reduce the quality of the process and the result [1]. The design of the robots each year is also getting advanced and more complex. Involved more accurate and more data collected to the processing purpose [2].

Robots need a motion source to move, motors are the most popular. There are numerous types of motion control systems: Stepper Motor, Brushless, Servo, and more. Ordinary DC motors are cheapest but less stable compared to other types of motors. And overshoot can be happened and will throw off the anticipated stop position even if the timing is just right. On the other hand, stepper can have high torque but at a slower rate. When the stator coil is energized, the electromagnetic field is produced at the rotor part that turns and rotates the rotor push against the stator that consists of the permanent magnet [3].
### Table 1. Pros and cons of stepper motor [3].

| Advantages                                      | Disadvantages                                      |
|------------------------------------------------|---------------------------------------------------|
| More efficient thanks to the brushless design  | Can be hot depending on the load and current needed.|
| Rotation angle is accurate and proportional to the input pulses. | Errors and oscillations can occur when pulse is missed under open-loop control.|
| High holding torque if the coils are energized | Lower torque at high speed or micro-stepping configuration.|

To be able to interact with the object it working with, the robot needs one or more mechanical parts that able to move and extend to specific positions that the operator or the system initially planned. One of the most used and most efficient is armed design [4]. The design was first bio-inspired of human hands of the multi, independent and function-rich design greatly increases the range of motion, output force and speed of a robot [5]. The arm robot was also been studied by many laboratories across the world to be able to perform various kind of tasks to replace works that too difficult or too dangerous to be done by human. Usually, many designs can be made to solve certain problems. The most important thing is how a part of the system can work with another part of the system and form a synergic system [6].

Data source are needed by a machine to be able to make a decision. It can be from any kinds of sensors, but not all sensors are equal in term of price/performance. 3D mapping nowadays can be achieved by many approach and sensors. For visual, there are ultrasonic ranging 3D mapping, Light Detection and Ranging (LiDAR), and 3D Mapping by Multiple camera setup [7]. To achieve multi-object at near real-time condition a camera setup is the most suitable for the condition of those. In many environments, various mass and sizes of objects are also necessary to able to accomplish certain jobs, sensors with high accuracy and resolution are required in an environment like this [8][9].

In a robot controller, a group of data are gathered from sensors, proceed by the computer and sent to the MCU to generate pulses to drives the motors. The motors then move accordingly as commanded. This kind of control is called inverse kinematic. The other is called forward kinematic which is given machines position data and calculate the final position. Inverse kinematics is more complicated since iteration calculations were made instead of direct numeric calculation. Hence, it’s more complicated and harder to accomplish and may have an error on the no rounded mathematics result [10]. The algorithm used in this research is FABRIK (Forward and Backward Reaching Inverse Kinematics). The main advantages of this algorithm are the minimum computational cost and visually realistic poses [11].

For the gripping part of the robot, many types of the method can be used. But in this research vacuum suction was used. According to recent research papers, a vacuum system is more efficient and faster than mechanical gripper, which also simpler and non-destructive [12]. The other biggest advantage of this system is, it can work with staged objects collided objects, which is impossible for gripper design due to the moving part [13]. The vacuum force can be generated with many types of machine. Vacuum pumps and air compressor are the most preferred solution due to the efficiency and power of the machine [14]. The power of the suction is also depended on the force generator itself. Which there is plenty of choices available in the market. Including AC or DC powered. Hence, this type of system usually called pick and place system [15]. Suction pad with material made of rubber, polyurethane and other materials are available on the market. Depend on the working environment, one could have better and worse than...
others. Then, a different form of suction cups is also available. Which also depend on surface area or object shapes, one could be better than others.

The overall system needed a sensor reader and pulses generator to be able to read from the sensors and calculate it and send a signal to the controller. Which, in this research, an STM32F108 microcontroller will be used to accomplish the necessary job. The reason is this microcontroller is currently widely available in the market at a cheap price point. Ease of programming also largely increase the research and development progress thanks to the user-friendly IDE [17].

2. Method
To be able to perform this research, a system of robotic arm with computer vision was designed. All the parts are easily purchasable and widely available in global market. All the software used in the design are open-sourced, thus, accessible and free for everyone.

| No. | Hardware/Software   | Specification/Version                      |
|-----|---------------------|--------------------------------------------|
| 1   | PC                  | 4Cores CPU 4GB RAM 64Bit                   |
| 2   | USB Camera          | 5MPX Resolution                            |
| 3   | Microcontroller     | STM32F108, 32bit                           |
| 4   | Drive System        | Belt drive with reduction gear set          |
| 3   | OpenCV2             | V 4.1.0                                    |
| 4   | Python              | V 3.6.0                                    |
| 5   | Tkinter             | V 8.6                                      |
2.1. Hardware design

Chassis of the robot was built with 3 mm acrylic, 2 sheet for each axis and 4 mm screw for connecting both sheets. Driven by 4 stepper motors with 4 moving parts:

| No. | Hardware/Software      | Description                                                                 |
|-----|------------------------|-----------------------------------------------------------------------------|
| 1   | Base/waist             | pulley ratio of 1:3 and ball bearing swivel plate to upper parts             |
| 2   | Lower Arm              | 20 cm, driven by planetary gearbox with ratio of 1:5.18 and pulley ratio of 1:3 |
| 3   | Upper Arm              | 30 cm, driven by stepper motor with pulley ratio of 1:3.                    |
| 4   | Working Arm            | 10 cm long with spring preloaded tubular pneumatic connector with rubber flat type suction cup. |
2.2. Software Design

The interface software is written in python with opencv2 as the main image processing libraries and make use of some other libraries to acquire necessary data. Steppers position data are also looped-back to the interface system just for monitoring and supervisory purpose.

The interface system needed a image input, a USB camera is used in this research, place 100 cm above to robot base. Connected via USB cable to the Image Processing and Interface Software written in python.

2.2.1. Image processing work flow.

The process stared with an image captured by the USB camera. Then, fed to the image processing program written in python with open library in able to extract the object coordinates. It works in a loop to be able to continuously grab frame from the camera. The system can work at near real time condition depend on the computer hardware. System work flow is shown with flowchart below.

![Figure 2. System / research apparatus.](image-url)
2.2.2. Inverse Kinematic Calculation.

The Kinematics Calculation is process using FABRIK (Forward and Backward Reaching Inverse Kinematics). After the target coordinate has calculated using previous algorithm. The value then feed into the kinetics calculation algorithm. The algorithm then calculate iteratively until the distance between target and calculated end-effector distance is smaller or equal to intended tolerance value. Which will be put into test in the research for the tolerance and time consumed.
3. Results and Discussion

Tests were made to each section of the system with various of parameter like lighting can affect the computer vision processing, object weight and shaped can affect arm robot positioning, object surface and delay time can affect the success rate of the pick-up process.

3.1. Computer Vision Coordinate Extraction

The image processing stage is tested in various light conditions. Each light condition, 30 frames of image were captured and measurement was made compare to the real center.

![Figure 4. Result comparison for various object parameters and lighting.](image)

| No. | Light Condition | Object Parameter | Tolerance Average |
|-----|-----------------|------------------|------------------|
| 1   | Low             | Dark Color, Single Color | 1-2 mm          |
| 2   | Low             | Multi-Color, dark and light | 2-4 mm          |
| 3   | Low             | Light, Single Color   | 1-2 mm          |
| 4   | Optimal/Normal  | Dark Color, Single Color | 1-2 mm          |
| 5   | Optimal/Normal  | Multi-Color, dark and light | 1-3 mm         |
| 6   | Optimal/Normal  | Light, Single Color   | 1-2 mm          |
| 7   | Overexposure    | Dark Color, Single Color | 1-2 mm          |
| 8   | Overexposure    | Multi-Color, dark and light | 1-2 mm         |
| 9   | Overexposure    | Light, Single Color   | 1-2 mm          |

3.2. Inverse Kinematics Processing

The algorithm then put into test with various tolerance value. The data to be collected are the tolerance, time consumed and final calculated distance. Table of data is shown below.

![Table 5. Inverse kinematics calculation.](image)

| No. | Test Coordinate | Max Tolerance | Calculated Tolerance | Time Consumed | Iteration |
|-----|-----------------|---------------|----------------------|---------------|-----------|
| 1   | 200, 80         | 0.1 mm        | 0.039 mm             | 890 ns        | 5         |
| 2   | 250, 60         | 0.1 mm        | 0.020 mm             | 650 ns        | 4         |
| 3   | 300, 50         | 0.1 mm        | 0.08 mm              | 430 ns        | 2         |
| 4   | 300, 50         | 0.05 mm       | 0 mm                 | 650 ns        | 3         |
| 5   | 250, 50         | 0.05 mm       | 0.039 mm             | 960 ns        | 4         |
| 6   | 180, 30         | 0.05 mm       | 0.03 mm              | 1 ms          | 9         |
3.3. Drop-off Accuracy
Due to the less rigid design and material of the apparatus. The robot accuracy will decrease with the increment of the object. This test was conducted with objects of various weight and surface area. Data is collected when arm reach the point right above object before drop-off and object position after dropped to the destination.

![Sample result comparison of different weighted objects.](image)

**Figure 5.** Sample result comparison of different weighted objects.

| No. | Object Parameter                  | Tolerance  |
|-----|-----------------------------------|------------|
| 1   | 100 gr, 10x15 cm surface area     | 1-1.5 mm   |
| 2   | 200 gr, 10x10 cm surface area     | 1.5-2.5 mm |
| 3   | 200 gr, 10x15 cm surface area     | 2-3 mm     |
| 4   | 300 gr, 10x10 cm surface area     | 2-3 mm     |

3.4. Pneumatic Pick-up Success Rate
The inertia moment of the motor can affect the success rate of pickup and drop-off rate of the test object. In this stage delay time before picking up various weight were tested. The data shown it the table below.

**Table 6.** Sample result of position feedback test.

| No. | Object Parameter                  | Delay Time | Success Rate |
|-----|-----------------------------------|------------|--------------|
| 1   | 100 gr, 10x13 cm surface area     | 0.5 s      | 100 %        |
| 2   | 200 gr, 10x10 cm surface area     | 0.5 s      | 99 %         |
| 3   | 300 gr, 10x10 cm surface area     | 0.5 s      | 99 %         |
| 4   | 300 gr, 10x10 cm surface area     | 1 s        | 99 %         |

*Red dot = Planned Target, white dot = real world position*
4. Conclusion
The system can pick and drop object at relatively high average rate. The computer vision processing system can analyze object centroid point at accuracy of 90% (1-2 mm). Kinematics calculation can reach accuracy within 1.5-3 mm of error within 10 iterations and 1 ms. Slippage occurrence rate is as low as 3% on object weighted 300gram at relative movement speed of 20°/second. The vacuum cup suction success rate is 99% on average on object weight 200-400 and delay time of 500 ms to 1s.

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