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DESIGN AND FABRICATION OF A 5 DOF DEXTEROUS ROBOTIC ARM FOR INDUSTRIAL TASKS

M.T. Islam[1], M. A. Wazed[1] and T. Mohammad[1]

[1]Department of Mechanical Engineering, Chittagong University of Engineering & Technology (CUET), Chittagong

ABSTRACT

In recent years the design, fabrication and development of dexterous robotic arms and robotic hands have been active research areas all around the world. This paper describes a mechanical system design concept and a prototype implementation of a 5 DOF jointed-arm robot, which should perform industrial task such as pick-and-place operation. This robot arm, being controlled by a microcontroller and interfaced to a computer, has base rotation, shoulder, elbow and wrist motion, and a functional gripper. Two-fingered gripper has been built as end effector and is capable of grasping diverse objects, even under external disturbances, within own workspace of the arm possible. Control of the robotic arm has been achieved successfully using six servo motors. The microcontroller implements inverse kinematics algorithms and position control on the motors. The design aims to provide fine manipulation in performing industrial tasks, while still maintaining the simplicity of design, miniaturization, and lightness are also achieved.

Keywords: Robotic arm, jointed-arm robot, robotic hand, mechanical system, fine manipulation.

1. INTRODUCTION

Jointed Arm robots are suitable for a wide variety of industrial tasks, ranging from welding to assembly. A jointed arm robot has some rotational axes connecting rigid links and a base. It is sometime called an anthropomorphic arm [1] because it closely resembles a human arm. It usually stands on a base on which it can rotate, while it can articulate at the “shoulder” joint, which is just above the base. The robot can also rotate about its “elbow” and “wrist” joints. These names match those of the corresponding human parts.

The “hand” of a robot is known as gripper, an end effector, an actuator, or end-of-arm tooling [2]. It consists of the driven mechanical devices attached to the end of the manipulator, by which objects can be grasped or acted upon. The robot may require a different type and design of hand for each different object to grasp or each different tool to build. In some cases, the hand itself acts as the tool [2]. Clearly, designing grippers properly is a key task in robotics.

Over the last few years, there has been much interest in the area of multi-fingered robot hands and dexterous manipulation. Dexterous multi-fingered end effectors are potentially ideal for applications requiring a combination of dexterity and versatility for grasping a wide range of objects [3]. The desire to design and construction of more dexterous hands has fueled an ongoing surge of activity in the areas of grasping and multi-fingered end effectors [4, 5]. Since the introduction of the groundbreaking and highly successful Stanford/JPL [6] and Utah/MIT [7] dexterous hand designs in the 1980’s, various robot hands have been designed, constructed, and tested. Concurrently, a significant body of work in synthesis and analysis of multi-fingered grasps has been built up. Surveys of these efforts can be found in a number of publications and texts, including [8, 9].

However, at this time, few dexterous hands have been successfully applied to practical applications. Many of the robot hands developed to-date have been complex, expensive, and/or bulky, featuring remote actuation via tendons, and have often not been physically robust, with reliability being a problem [10]. Currently, there is a strong interest in developing simpler, more ‘minimalist’ hand designs [8]

This paper describes a mechanical system design concept and a prototype implementation of a 5 DOF jointed-arm robot, which should perform industrial task such as pick-and-place operation. The design aims are to provide fine manipulation in performing industrial tasks, while still maintaining the simplicity of design, miniaturization, and lightness.

2. GENERAL STRUCTURE OF ROBOT ARM AND ROBOT HAND

A robot arm or a robot hand can be split up in two major subsystems [11]:

(1) The mechanical system
(2) The control system

2.1. Mechanical system

The mechanical system describes how the arm and hand look like and what kind of components they are made of. It defines the mechanical design, e.g. the number of fingers and the kind of materials used. Additionally actuators, e.g. electric motors, and sensors, e.g. position encoders, are settled [11]. The mechanical system can be subdivided into:

(1) The mechanical design
(2) The actuator system
(3) The sensor system

The mechanical design determines the fundamental 'dexterousness' of the arm and hand, i.e. what kind of objects can be grasped and what kind of manipulations can be performed with a grasped object [11]. Three basic aspects have to be settled when designing a robot hand [11]:

(1) The number of fingers
(2) The number of joints per finger
(3) The size and placement of the fingers

To be able to grasp and manipulate an object safely within the workspace of the hand at least 2 fingers are required. However, to be able to re-grasp an object without having to release it and then pick it up again, at least 4 fingers are necessary [11]. To determine the size and the placement of the fingers two different approaches can be taken [11]:

(1) Anthropomorphic
(2) Non-anthropomorphic

It then depends on the objects to manipulate and on the type of manipulations desired which one is chosen. An anthropomorphic placement allows to easily transferring e.g. grasp strategies from a human hand to the robot hand [11]. But the different size of each finger and their asymmetric placement makes the construction more expensive and the control system more complicated, because each finger has to be treated separately. When a non-anthropomorphic approach is taken most often identical fingers are arranged symmetrically. This reduces the costs for the construction and simplifies the control system because there is only one single 'finger module' to be constructed and controlled [11].

The actuation of the finger joints also has a great influence in the dexterousness of the hand, because it determines the potential forces, precision and speed of the joint movements. Two different aspects of the mechanical movement have to be considered [11]:

(1) Movement generation
(2) Movement forwarding

Several different approaches for these aspects are described in the literature. E.g. the movement can be generated by hydraulic or pneumatic cylinders or, as in most cases, by electric motors [12]. As the movement generators (motors) are in most cases to big to be integrated in the corresponding finger joint directly, the movement must be forwarded from the generator (most times located in the last link of the robot arm) to the finger joint. Again different methods can be used, like tendons [13, 14], drive belts [15, 16] or flexible shafts. The use of such more or less indirect actuation of the finger joint reduces the robustness and the precision of the system and it complicates the control system because different joints of one finger are often mechanically coupled and must be decoupled in software by the control system. Due to these drawbacks an integration of miniaturized movement generators directly into the finger joints is desirable.

Servos are DC motors with built in gearing and feedback control loop circuitry [2]. Servos are extremely popular with robot, RC plane, and RC boat builders. Most servo motors can rotate about 90 to 180 degrees. Some rotate through a full 360 degrees or more. However, servos are unable to continually rotate, meaning they can't be used for driving wheels unless modified, but their precision positioning makes them ideal for robot legs and arms, rack and pinion steering, and sensor scanners to name a few. Since servos are fully self contained, the velocity and angle control loops are very easy to implement, while prices remain very affordable. To use a servo, the black wire is connected to ground, the red to a 4.8-6V source, and the yellow/white wire to a signal generator such as from microcontroller [2].

2.2. Control system

The control system of a robot arm determines which of the potential dexterous skills provided by the mechanical system can actually be exploited. An automatic control system is used to carry out the instructions stored in the robot’s memory. Without the automatic control system, the robot would just be a remote-controlled device. Automatic control systems are of two types: open-loop and closed-loop controlled system. The open-loop non-servo-controlled system assumes that everything is working and does not check the robot’s orientation. It is sometimes referred to simply as a non-servo-controlled system. The closed-loop servo-controlled system senses where the manipulator is and corrects its position as needed. The closed-loop servo control can function in either a point-to-point or a continuous-path mode of operation. Closed-loop servo-controlled systems are sometimes referred to simply as servo-controlled systems [2].

The control system must meet several conflicting requirements [11]:

(1) Many input/output resources like actuator or sensor signals must be attached. For example for a minimum hand with 5 degrees of freedom, at least 5 analog outputs to the motors must be estimated. With force and tactile sensors for every finger and additional object state sensors, the number of inputs quickly increases to several dozens.

(2) Quick reactions in real-time to external events are required. If for example a slipping of the grasped object is detected immediate counter measures must be taken.

(3) High computing power for several different tasks must be available. For example path planning, coordinate transformations, closed loop control in software are executed in parallel for multiple fingers as well as for the object.

(4) Small physical size is needed to be able to integrate the control system into the manipulation system.

(5) Short electrical connections between the control system and the actuators and sensors should be used. This is especially relevant for the sensors because otherwise massive interference might disturb the sensor signal.

(6) The control system consists of the control hardware and the control software [11]. The control software of a robot arm and hand is quite complex. Several joints must be controlled in real-time and in parallel while new trajectories for the fingers and the object must be planned at the same time. Therefore it is necessary to reduce the complexity by dividing the problem into sub problems. Another aspect concerns software development. As a robotic arm is usually a research project for most of its lifetime, the programming environment, like user interface, programming tools and debugging facilities, should be powerful and flexible. This can only be achieved if a standard operating system is used [11].

To cope with the requirements the control hardware is usually distributed among several specialized processors. For example the input/output on the lowest level (motors and sensors) can be handled by a simple microcontroller, which is also of small size and thus can be integrated more easily into the manipulation system. But the higher levels of control need more computing power and the support of a flexible real time capable operating system. This can be achieved most easily with PC-like components. Therefore the control hardware often consists of a non-uniform, distributed computing system with microcontrollers on the one end and more powerful processors on the other [11]. The different computing units then have to be connected with a communication system, like for example a bus system.

The microcontroller used in this project is SSC-32 (Fig. 1). Servo Move example: "#5 P1600 T1000 <cr>". This command will move servo 5 to position 1600. It will take 1 second to complete the move regardless of how far the motor has to travel to reach the destination. Up to 32 motors can be driven from this controller. This device is also designed to supply power to the control system.

3. DESIGN AND CONSTRUCTION

3.1 Robotic Arm Specifications

(1) Jointed-arm Robot

(2) Degree of freedom (DOF) = 5

(3) Shoulder, elbow and wrist motion, and gripper actuation

(4) Base rotation but no wrist rotation

(5) Reach (forward) = 254mm - 304.8mm

(6) Range of motion per axis = 180°

(7) 6 servomotors: one for the base, two for the shoulder, and one each for the elbow, the wrist and the gripper.

(8) Lift weight (arm extended) = max. 100 gm

3.2 Calculation for motor selection:

After mechanical structure of the robot manipulator is determined, a suitable scheme for producing motion is developed. Here we are concerned primarily with peak and maximum continuous torque calculation method for selecting the servo motors that drive the individual joints of the jointed-arm robot. The length and the mass of different components are given below:

Mass of forearm links = 100 g
Mass of upper-arm links = 100 g
Mass of wrist links and gripper plate= 50 g
Mass of gripper = 50 g
Length of forearm links = 12 cm
Length of upper-arm links = 15.5 cm
Length of wrist links = 5.5 cm
Length of gripper = 10 cm

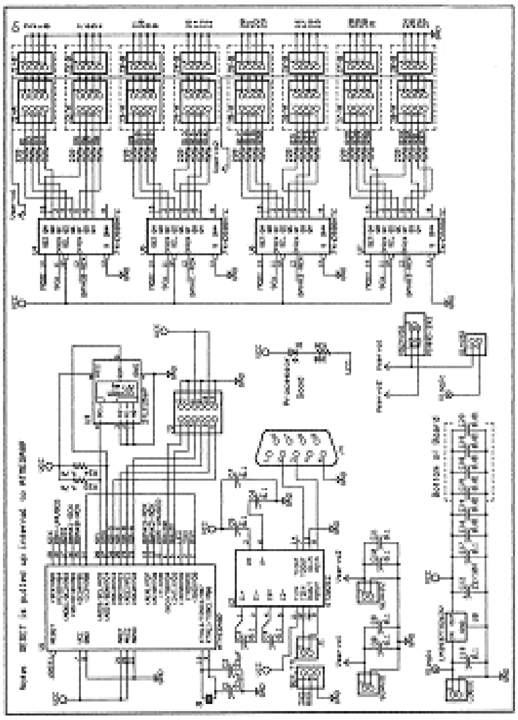


Fig 1: Circuit diagram of microcontroller SSC-32

The basic equation is moment equals force times the distance of the body the force is being applied perpendicularly at.

$$\text{Moment} = \text{Force} \times \text{distance} \qquad (1)$$

Therefore, the calculated torque at each joint of the robot arm:

Gripper $= 0.05\times (10/2) = 0.25$ kg-cm $= 0.0245$ N-m

Wrist $= 0.05\times (5.5/2) + 0.05\times (10/2 + 5.5) + 0.01644\times 5.5 = 1.415$ kg-cm $= 0.1388$ N-m

Elbow $= 0.1\times (15.5/2) + 0.05\times (5.5/2 +15.5) + 0.05\times (10/2 + 5.5 + 15.5) + 0.1644\times (15.5+5.5) + 0.04706\times 15.5= 4.0625$ kg-cm $= 0.3985$ N-m

Shoulder $= 0.1\times (12/2) + 0.1\times (15.5/2 + 12) + 0.05\times (15.5 + 12+ 5.5/2) + 0.05\times (12 + 15.5 + 5.5 + 10/2)+0.04706\times 12+0.04706\times 15.5 +0.01644\times (15.5+5.5+12) = 7.72$ kg-cm $= 0.7573$ N-m $= 2 \times 0.3787$ N-m, [Since 2 motors at the shoulder]

Therefore, the arm includes five Hitec HS-422 servo motors. A Hitec HS-81 is included for the gripper.

3.3 Design of the Base

The design of base of the robot allows it to support the arm. Rotating base panel, lower base panel, and upper base panel have been designed and built as shown in Fig. 2. The rotating base is connected with base motor and thereby can rotate +/- 90 degrees from its mid position for a total of 180 degrees of rotation.

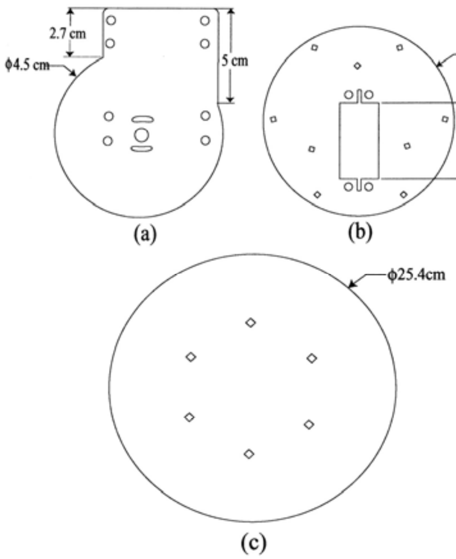


Fig 2: Base Panels: (a) Rotating base panel, (b) Lower base panel, and (c) Upper base panel

3.4 Construction of the Base

The motor into the top panel is installed using rivet fasteners. Then the hex spacers are installed by using screws and nuts. This is the bearing surface for the base rotate panel. Now the longer hex spacers are installed by using screws and the bottom panel onto the base structure is installed, as shown in Fig. 3, by using screws and tightening these down snugly. While the motor is centered, the rotating base is installed as illustrated in Fig. 3.

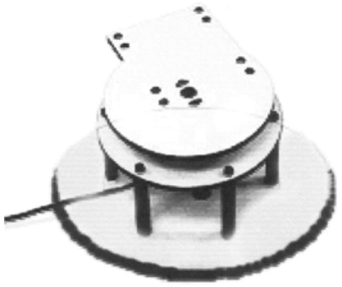


Fig 3: The stationary base of the arm

3.5 Design of the Arm

The aim of the forearm and upper arm design was to develop a light-weight arm with a slim and compact type of construction. The design allows a space-saving arrangement of the motors and has the advantage that moment of inertia according to the longitudinal axis of the forearm is very low.

3.6 Construction of the Arm

Upper arm links and forearm links have been designed and built as illustrated in Fig. 4. Now the forearm structure is assembled with the help of screws and hex spacers. The wrist and elbow motors are attached with the links so that the motors are sandwiched in between the forearm links as shown in Fig. 5. The arm upright links are attached to the motors as presented in Fig. 6. Then the forearm is attached to the uprights as shown in Fig. 7. This completes the construction of the basic arm.

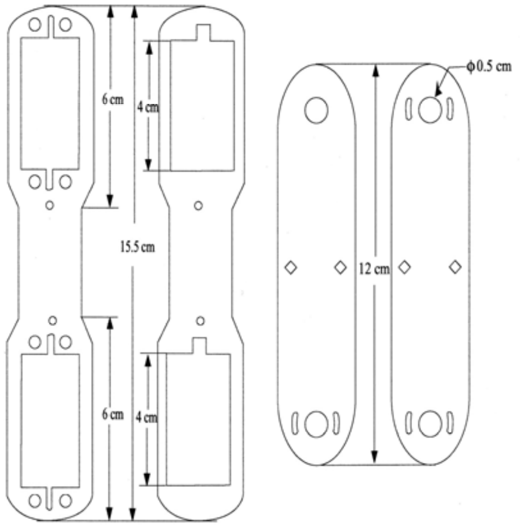


Fig 4: Arm Links: (a) Upper Arm Links and (b) Forearm Links

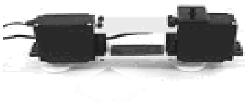


Fig 5: Forearm structure

Fig 6: Upper arm structure

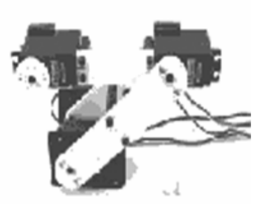


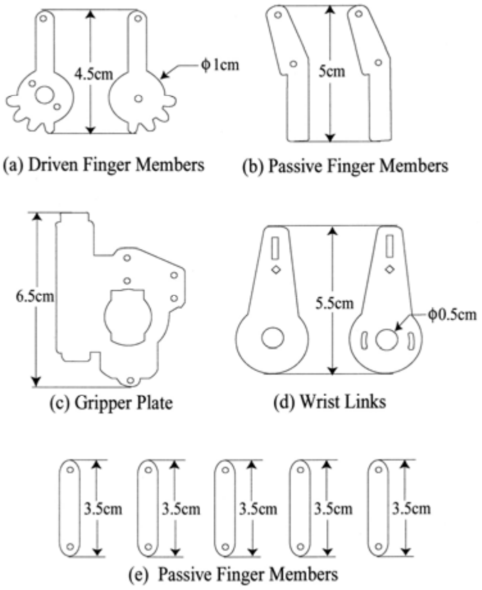
Fig 7: The basic arm structure

3.7 Design of the gripper

The gripper consists of driven finger members and 7 passive finger members. The wrist consists of 2 wrist links and a gripper motor plate. The design allows a space-saving and cheap construction (Fig. 8).

3.8 Construction of the gripper

Wrist links are connected to the gripper motor panel/plate as illustrated in Fig. 9 by using screws. Then the driven gripper member is installed to the motor using two tapping screws. The passive gripper finger members and other fingers are attached as illustrated in Fig. 10. For each position with a screw is inserted into the top cross gripper finger (Fig. 11), another washer is added through the lower cross member, then it is finished off with a nut.



(a) Driven Finger Members (b) Passive Finger Members

(c) Gripper Plate (d) Wrist Links

(e) Passive Finger Members

Fig 8: Wrist links and Gripper members

Fig 9: Wrist structure

Fig 10: The gripper construction

Fig 11: The gripper

3.9 Assembling

The ball bearing is installed to the wrist motor hinge. Then the gripper is installed onto the arm using tapping screws and washers. Now the arm is attached to the stationary base using four screws and the lock nuts. Therefore, the gripper, arm and base are assembled. Thus the construction of robotic arm is completed as shown in Fig. 12. The first joint above the base is referred to as the shoulder. The shoulder joint is connected to the upper arm, which is connected at the elbow joint.

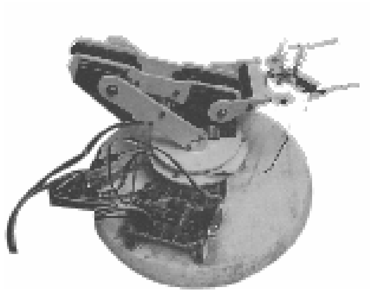


Fig 12: The complete robotic arm

The following step deals with wiring. As the base is stationary, the servo cable is run out and plugged into channel 0 of the controller. Now the cables of two shoulder motors are plugged into channel 1 of the controller. Similarly, the elbow motor, the wrist motor, and the gripper motor are plugged into the controller channel 2, 3, and 4 respectively. A serial data cable is used to interface the microcontroller with computer.

4. RESULTS AND DISCUSSION

Up to now a robotic arm having stationary base and functional gripper has been built up. Six motors provide five active degrees of freedom (Fig. 13) to complete structure of the robotic arm. The arm is used to move the hand within reach of a part or work piece. The base of the robot serves to support the arm and the arm can rotate about the shoulder.

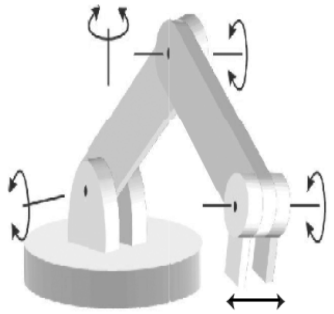


Fig 13: 5 degrees of freedom of the arm

The wrist of the robot aims the gripper at any part or work piece. The wrist provides pitch (up-and-down) motion. The driven finger member is attached to the horn of gripper motor, while its torque allows each finger to move dependent of other. Thus both fingers move together during grasping, holding and releasing objects.

To evaluate the performance and motion abilities of the robotic arm, an objective of performing easy industrial application such as a pick-and-place operation was selected. At the same time, to validate the capability of the gripper, two objects of different size, shape, and weight were chosen. One object is a rectangular box weighting 50g (Table 1 and Fig. 14). Another object is round ball weighting 100g (Table 2 and Fig. 15). These reveal the capability of the arm to perform fine manipulation tasks.

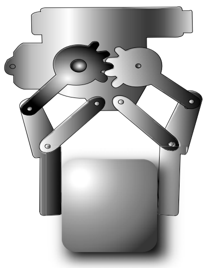


Fig 14: Gripper grasping rectangular object

The robotic arm has a load bearing capacity of 100 gm and a maximum workspace of 304.8 mm along the horizontal plane.

Moreover, robotic arm should be flexible enough to do several tasks and thereby capable of adaptation to substantially changed production requirements. This structure is flexible and has ability to reach over obstructions. It can generally achieve any position and orientation within the working envelope. Another advantage of the arm is that it is light. It does not have any complex mechanical components to make itself too heavy. Most of the weight will be taken over by the motors and links, followed by the object grasped.

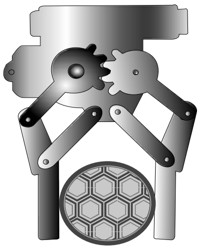


Fig 15: Gripper grasping spherical object

Table 1: Moving rectangular object (50 gm)

Step	Base Angle	Shoulder Angle	Elbow Angle	Wrist Angle	Grip Angle	Grip Opening (cm)
1	-35.77°	3.39°	-20.94°	23.26°	20°	5.36
2	-35.77°	3.39°	-20.94°	23.26°	81.6°	3.84
3	-35.77°	-21.09°	-20.94°	23.26°	81.6°	3.84
4	-35.77°	-21.29°	-21.33°	30.74°	81.6°	3.84
5	90°	-21.29°	-21.52°	30.74°	81.6°	3.84
6	90°	-21.5°	-46.09°	30.94°	81.6°	3.84
7	90°	-21.7°	-46.67°	31.35°	20°	5.36
8	90°	-21.7°	-15.09°	31.35°	20°	5.36
9	-51.23°	-21.91°	-15.28°	31.55°	20°	5.36
10	-35.77°	-4.63°	15.91°	13.15°	20°	5.36

Table 2: Moving spherical object (100 gm)

Step	Base Angle	Shoulder Angle	Elbow Angle	Wrist Angle	Grip Angle	Grip Opening
1	-35.77°	-6.27°	-9.43°	21.03°	20°	5.36
2	-35.77°	-3.81°	-12.36°	21.44°	29.8°	3.84
3	-35.77°	-2.57°	13.57°	-5.87°	29.8°	3.84
4	83.08°	-2.16°	-5.14°	12.54°	29.8°	3.84
5	83.8°	-2.57°	12.4°	-4.65°	29.8°	3.84
6	83.08°	-4.83°	-2.22°	12.34°	20°	5.36
7	83.08°	-5.66°	18.64°	-7.69°	20°	5.36
8	-34.85°	-5.66°	18.64°	-7.69°	20°	5.36
9	-34.85°	-6.07°	-5.73°	19.62°	20°	5.36
10	-35.77°	-9.77°	-17.04°	24.88°	20°	5.36

5. CONCLUSIONS

From this design of dexterous robotic arm and gripper with non-anthropomorphic fingers, the following conclusion can be drawn:

(1) To be able to perform dexterous fine manipulations with a robot hand a suitable mechanical system and control system is necessary.

(2) This robot hand is capable of grasping a wide variety of objects of different shape, size and weight. The pose of a grasped object can be controlled reliably, even under external disturbances.

(3) Shorter link lengths are better in that they are bend less, allowing higher accuracy and less flopping around and they require less torque to move, and hence smaller/cheaper motors. Shorter link lengths are worse in that they have a shorter reach and can only work with smaller parts.

(4) Installing a robot won't work or solve all quality problems unless the robot is not programmed correctly, the parts are not designed exactly, the piece parts are not made accurately, or the objects are not properly presented to the robot.

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