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FABRICATION AND PERFORMANCE OF A TWO-LINK SCARA ROBOT

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Abstract*-The present work reports the fabrication and performance of a two-link SCARA robot. The arm of the robot is compliant in x-y plane, but rigid in 'z' plane. It was fabricated with locally available material at low cost. Necessary circuitry and computer program were developed to drive two stepper motors with a view to rotating the links via a computer's parallel port interface. Inverse kinematics was used to solve the desired rotary motion of the links. Consequently, the robotic arm is used to locate any polar coordinate within its work envelope.*

Keywords: SCARA robot, Inverse kinematics, Stepper motor, Drive circuitry, PC interfacing

1. INTRODUCTION

In the recent years automation has had a notable impact in a wide range of industries. Nearly all industrial installations of automation, and in particular robotics, involve a replacement of human labor by an automated system. A machine used to perform jobs automatically, which is controlled by a computer, is known as robots [1]. Jobs, which require speed, accuracy, reliability or endurance, can be performed far better by a robot than human. Robots have replaced humans in the assistance of performing those repetitive and dangerous tasks which humans prefer not to do, or are unable to do due to size limitations, or even those such as in outer space or at the bottom of the sea where humans could not survive the extreme environments. For example, the recently launched 'Curiosity Robot' epitomizes the most advanced payload of scientific gear ever used on the Martian surface. The robot's arm designed to survive the large temperature changes in space also bears the reputation of being a critical mechanism to this mission.

A mechanical robotic arm, usually programmable, has similar functions like a human arm. The links of such a manipulator are connected by joints allowing either rotational motion, such as in an articulated arm or translational displacement. The links of the manipulator can be considered to form a kinematic chain. The business end of the kinematic chain of the manipulator is called the end-effector and it is analogous to the human hand. The Selective Compliant Articulated Robot Arm, better known as SCARA perfectly exemplifies these helping hands. The principle function of this robotic arm is to locate any polar coordinate within its work envelope. With speed, cost effectiveness, dependability and a small footprint working in its favor, the SCARA may be used for any jobs involving point to point movements like dispensing, loading, pick and place, assembling and palletizing. The latest generation of SCARA robots offers improved intelligent and streamlined parts count, as well as other features like heavier payload capacity, simple cabling and smaller space requirements.

By virtue of the SCARA's parallel-axis joint layout, the arm is slightly compliant in x-y plane but rigid in 'z' direction, hence the term: Selective Compliant [2-3]. This is advantageous for many types of assembly operations. The second attribute of the SCARA is the jointed two-link arm layout similar to human arms, hence the term, Articulated. This feature allows the arm to extend into confined areas and then retract or 'fold-up' out of the way. This is advantageous for transferring parts from one cell to another or for loading/unloading process stations that are enclosed. SCARAs are generally faster and cleaner than comparable Cartesian system. On the contrary, these may be more expensive than comparable Cartesian systems as the controlling program requires direct kinematics for linear interpolated moves.

The main objectives are to fabricate a SCARA robot with low cost locally available materials and to observe the performance after completion of work. The SCARA has two links connected to each other and assembled with respect to the center of a rigid base. A power supply circuit and a motor controlling circuit were built to run the stepper motors which are connected to the joints respectively. To materialize the whole plan, the works need to be classified into two kinds. So the components necessary to make the robotic arm can be generally classified into two categories- 1) Mechanical components and 2) Electrical and electronic components.

2. MECHANICAL COMPONENTS

The robotic arm is to run by using the rotational motion of the stepper motors. In this case the driving motors get pulses from the motor driver circuit that allows precise control of the motors through computer's parallel port. The motors used must be capable of carrying higher loads. But to make the structure lighter the motors chosen were of low capacity. So efforts were made to make the body structure lighter. At the same time the material of SCARA was chosen strong enough to resist the bending effect of the links while rotating.

2.1 Body Structure

To make the body light and stronger, the arm links were made of thick nylon sheets. This was to ensure that the links are not heavy for the structure and for easy mobility. Nuts and bolts were used for temporary shoulder and elbow joints of the links. In this project, mainly 3/16" nuts and bolts were used.

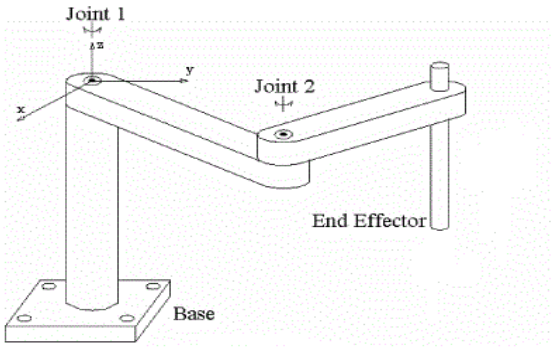

Fig.1: Schematic diagram of SCARA body structure

2.2 Stepper Motor Operation

A stepper motor is a brushless synchronous electric motor that divides a full rotation into a large number of steps. It converts electrical pulses into specific rotational movements. The movement created by each pulse is precise and repeatable, which is why stepper motors are so effective for positioning applications that this robotic arm is meant to do. There are different kinds of steppers available, all with different characteristics. Coil resistance, torque ratings, step angle, number of phases, voltage ratings, etc. are all characteristics to be considered when designing a stepper motor system. In our project four-phase unipolar stepper motors were used.

In the construction of unipolar stepper motor there are four coils. One end of each coil is tied together and it gives common terminal which is always connected with positive terminal of supply. The other ends of each coil are given for interface.

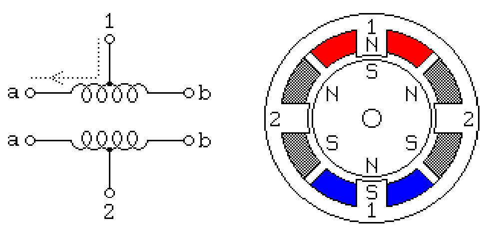

Fig.2: Operation of unipolar stepper motor

The relationship among step angle, rotor teeth, and stator teeth is expressed using the following equation:

$$\varphi = \left[\left(N_s - N_r \right) / N_s N_r \right] \times 360° \qquad (1)$$

Where, φ is the step angle in degrees, N_s is the number of teeth on stator core and N_r is the number of teeth on rotor core.

Stepper motors are also rated in terms of the number of steps per second which is known as the stepping rate. The actual speed of a stepper motor is dependent on the step angle and step rate and is found using the following equation:

$$N = \left[\varphi (s/s) \right] / 6 \qquad (2)$$

Where, N is the motor speed in RPM and s/s is the number of steps per second.

3. ELECTRICAL AND ELECTRONIC COMPONENTS

3.1 ULN 2003

The ULN2003 is a monolithic high voltage and high current Darlington transistor arrays. It consists of seven NPN Darlington pairs that feature high-voltage outputs with common-cathode clamp diode for switching inductive loads. The collector current rating of a single Darlington pair is 500mA. The Darlington pairs may be paralleled for high current capability. Salient features of ULN2003 IC are as follows:

- ULN2003 has a 2.7kΩ series based resistor for each Darlington pair, allowing operation directly interfaced with computer using parallel port.
- ULN2003 is the original high voltage, high current Darlington array. The output transistors are capable of sinking 500mA and will sustain at least 50V in the off state. Output may be paralleled for higher current capability.
- ULN2003 Darlington arrays are furnished in a 16-pin dual in line plastic package. These are also be supplied in a hermetic dual in-line package.

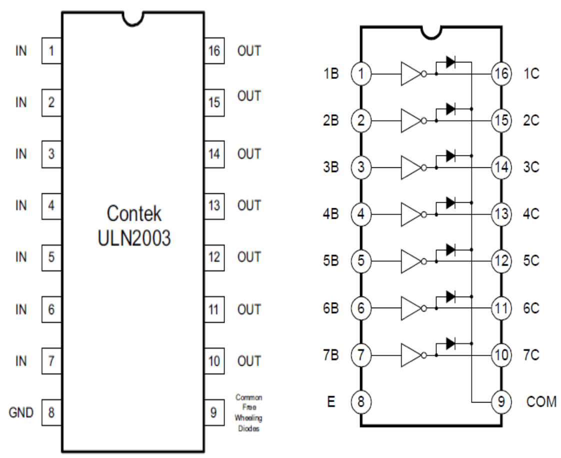

Fig.3: ULN 2003 pin configuration and logic diagram

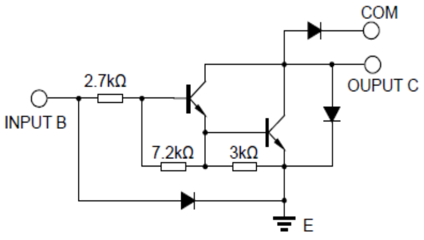

Fig.4: Schematic of each Darlington pair

ULN2003 is a dedicated IC for driving high current. In this project, there were two ULN2003 used to control two stepper motors each of 5V individually.

3.2 Transformer

In this project a center-tapped step down transformer was used to convert the supply voltage into 18V. Its current rating was 4.5A.

3.3 IC 7805

It is a power mosfet or linear voltage regulator IC that is necessary to give a precise 5V power supply for the digital system. Salient features regarding this IC are as follows:

- This IC does not require additional components to provide a constant, regulated source of power, making it easy to use, as well as economical and efficient uses of space. Other voltage regulators may require additional components to set the output voltage level, or to assist in the regulation process.
- It has built-in protection against a circuit drawing too much power.

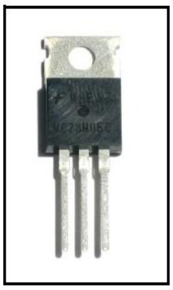

Fig.5: Pin configuration of IC 7805

4. INVERSE KINEMATICS

Robot kinematics is the study of robot motion without regards to the forces that result in. The inverse kinematics deals with the problem of finding the appropriated joint angles to get a certain desired position and orientation of the end-effector [6-7]. Finding the inverse kinematics solution for a general manipulator may be a very tricky task. In general, inverse kinematics solutions are not linear. To find those equations may be complicated and sometimes there is no solution for the problem. Trigonometric method is provided in this section for solving inverse kinematics of SCARA.

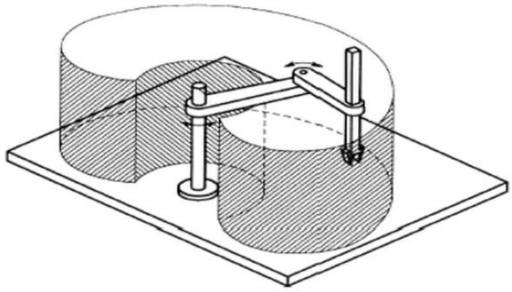

Fig.6: SCARA Manipulator Kinematics

The inverse kinematics problem is much more interesting and its solution is more useful. At the position level, the problem is stated as, “Given the desired position of the robot’s hand, what must be the angles at the entire robots joints?”
One of the simple ways to solve the inverse kinematics problem is by using trigonometric solution. With this method, cosines law is used. A two planar manipulator to solve the inverse kinematics problem is given in the following figure:

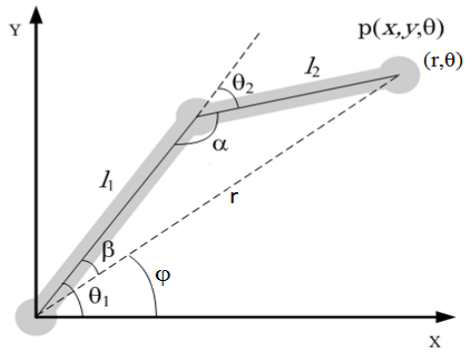

Fig.7: Geometry of two-link planar SCARA robot

Here’s the statement of the inverse kinematics problem at the position level of this robotic arm,
Given: r, φ
To find: θ_1, θ_2

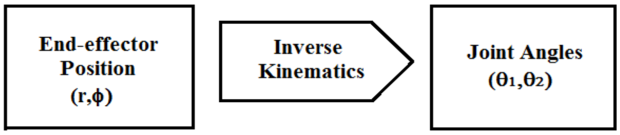

Fig.8: Inverse kinematics diagram

To solve this inverse kinematics, trigonometric method has been applied to solve for a joint variable. Once the joint variable is solved, the manipulator could be considered as a reduced degree of freedom (DOF) mechanism- with one less joint. From fig. 7, the geometric and trigonometric equations are found as follows:

$$r^2 = x^2 + y^2 \quad (3)$$

$$\varphi = \mathrm{a}tan2\,(y,x) \quad (4)$$

$$\beta = cos^{-1}\,[(l_1^{\,2} - l_2^{\,2} + r^2)/2l_1r] \quad (5)$$

$$\theta_1 = \varphi + \beta \quad (6)$$

$$\alpha = cos^{-1}\,[(l_1^{\,2} + l_2^{\,2} - r^2)/2l_1l_2] \quad (7)$$

$$\theta_2 = 180^{o} - \alpha \quad (8)$$

where, (r, φ) is the polar coordinate of the end-effector, (x,y) is the Cartesian coordinate of the end-effector, l_1 and l_2 are the length of the inner and outer link respectively, θ_1 is the interior angle between the x-axis and the inner link, θ_2 is the exterior angle between the two links, α is the interior angle between the two links, and β is the interior angle between the inner link and the imaginary straight line that extends from the robotic arm's inner joint to its outer joint.

There are multiple solutions to the inverse kinematics problem. The existence of multiple solutions adds to the challenge of the inverse kinematics problem. Typically it is required to know which of the solutions is correct. All programming languages that are typically known of supply a trigonometric function called 'atan2' that will find the proper quadrant when given both the x and y arguments: atan2 (y,x).

That completes the solution for θ_1 and θ_2 given r and ϕ. The solution given above works as is for the SCARA. The inverse kinematics solution is trivial as all axes are perpendicular by definition and thus there is no coupling of the motions.

To summarize the numerical approach to solving the inverse kinematics problem for the SCARA, the following diagram demonstrates a simple solver:

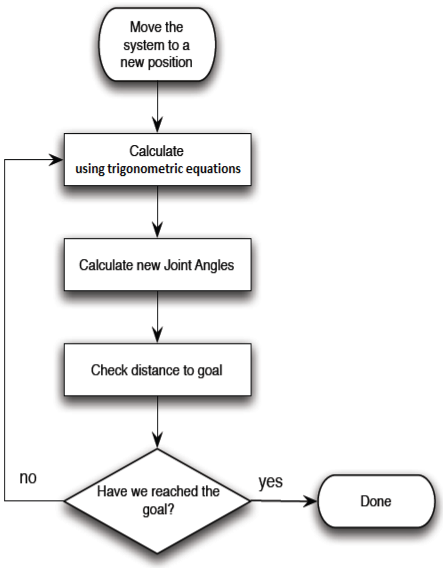

Fig.9: Flow chart of inverse kinematics solver for SCARA

5. STEPPER MOTOR CONTROLLING MECHANISM

Resistors cannot draw more than a few milliamps of current. Therefore, to drive the stepper motors, devices are essentially needed that could withstand fast current switching [8-9]. A ULN2003 n-p-n Darlington transistor array is such a device. A 5V regulated power supply circuit with IC 7805 was used as the maximum rated voltage of these stepper motors were 5V per phase.

5.1 Power Supply Circuit

This is a small +5V regulated power supply circuit. IC 7805 was used for the purpose. The circuit had internal current limiting and thermal protection. An 18V 4.5A step down transformer was used to convert 230V to 18V from mains. Here used a bridge rectifier made by four 1N 4007 diode to convert AC to DC. 470µF 50V as C1 was used for filtering. As 500mA current was needed at output, a heat sink was used with the 7805 IC. The circuit diagram is given below.

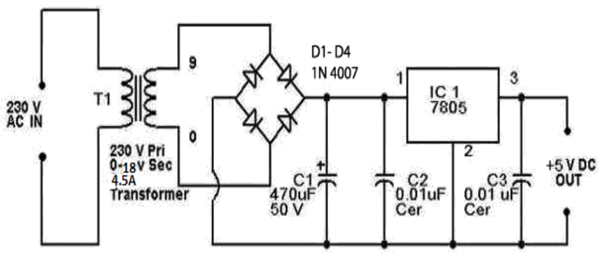

Fig.10: 5V regulated power supply circuit diagram

5.2 Motor Driver Circuit

In able to move the rotor of the motors, a driver is needed. Driver is a circuit that applies a voltage to any of the four stator coils. In this project, the driver was built with two ULN2003 ICs to drive two stepper motors individually.

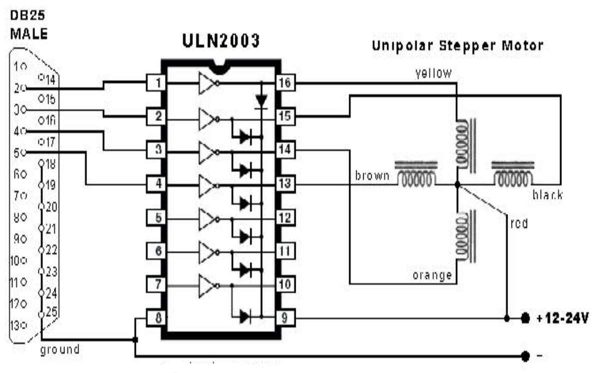

Fig.11: Motor driver circuit diagram with ULN2003 IC

Motor coils require a sequence of alternating current phases. There are three different modes to operate the stepper motors by applying pulses. The table given below gives the complete idea that how to give pulses in each mode:

Table 1: Stepping modes

Single Coil Excitation		Double Coil Excitation	
Clockwise	*Anticlockwise*	*Clockwise*	*Anticlockwise*
L4 L3 L2 L1	*L4 L3 L2 L1*	*L4 L3 L2 L1*	*L4 L3 L2 L1*
0 0 0 1	0 0 0 1	0 0 1 1	0 0 1 1
0 0 1 0	1 0 0 0	0 1 1 0	1 0 0 1
0 1 0 0	0 1 0 0	1 1 0 0	1 1 0 0
1 0 0 0	0 0 1 0	1 0 0 1	0 1 1 0
Half Step Excitation			
Clockwise		*Anticlockwise*	
L4 L3 L2 L1		*L4 L3 L2 L1*	
0 0 0 1		0 0 0 1	
0 0 1 1		0 0 1 1	
0 0 1 0		1 0 0 0	
0 1 1 0		1 0 0 1	
0 1 0 0		0 1 0 0	
1 1 0 0		1 1 0 0	
1 0 0 0		0 0 1 0	
1 0 0 1		0 1 1 0	

In this project, the stepper motors used were of 1.8^o step angle. Therefore, for single coil excitation 200 pulses were needed to complete one revolution as each pulse moves rotor by 1.8^o. From table I, it is seen that the given sequence had to be repeated 50 times for motor to complete one revolution.

5.3 Computer Interface and C Programming

Computer's parallel port is ideally suited for signal transmission [10]. For this purpose, DB 25 pin male port was used in this project. Salient features are given below in this regard:

- The port's addresses must be known. Data are needed to be written out with a C program. PCs have three basic types of internal ports:
  - Data- 8 data signals possible (D0-D7)
  - Status- 5 input signals
  - Control- 4 signals
- C coding is used for motor control that
  - Controls pulse sequence to motor.
  - Provides position of motor at all times.
  - Gives user the choice of direction to turn and degree increments.
- The inverse kinematics solver above mentioned is written out with the C program accordingly.

5.4 System Block Diagram For Controlling Stepper Motor

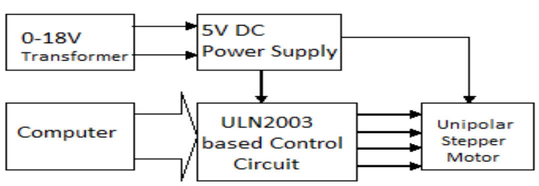

Fig.12: System block diagram for controlling unipolar stepper motor

6. SCHEMATIC DIAGRAM OF FULL PROJECT

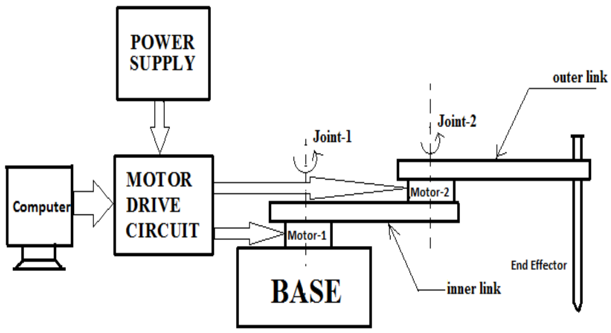

Fig.13: Schematic diagram of full SCARA project

7. RESULT

The SCARA robot has been found quite reliable and precise. A scaled work envelope highlighting different polar coordinates at different corresponding locations was previously made where the base of the robotic arm was set on top of it at the center. Few attempts were made to monitor the results. The arm end-effector reached the desired polar coordinates each and every time. The results would have definitely been more précised if stepper motor of smaller step angles were used.

8. SUMMARY

From industrial perspective, SCARA has always been an ideal choice for numerous applications such as pick and place work, application of sealant, assembly operations and handling machine tools. Some points may summarize the whole work as follows:

- The SCARA robot was fabricated with locally available materials with a view to making it a cost-effective automated tool.
- Robot kinematics techniques and motor controlling mechanisms along with different driving circuitry have been analyzed and applied effectively. Inverse kinematics

Among the robot kinematics methods, inverse kinematics has been used to solve the kinematics of the SCARA robot. For the purpose, trigonometric method is applied.

9. RECOMMENDATIONS FOR FUTURE WORK

From the perspective for improving this project, few recommendations are as follows:

- Addition of extra link in 'z' direction may make the SCARA robot more universal.
- A fourth axis of motion which is the wrist rotation may also be incorporated in future in order to make the SCARA more effective.
- A microcontroller may be used instead of pc interfacing for easy operation.
- More careful choice of material for the body structure, the performance of SCARA may have been improved.

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11. NOMENCLATURE

Symbol	Meaning	Unit
ϕ	Step angle	(degree)
N_s	Stator teeth number	
N_r	Rotor teeth number	
s/s	Number of steps per second	
N	Motor speed	(rpm)
(r, φ)	Polar coordinate	
(x/y)	Cartesian coordinate	
l_1	Length of inner link	(m)
l_2	Length of outer link	(m)
θ_1	Interior angle between x-axis and inner link	(degree)
θ_2	Exterior angle between two links	(degree)
α	Interior angle between two links	(degree)
β	Interior angle between inner link and imaginary straight line	(degree)