Design and development of robot for harvesting cotton bolls

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Abstract: Most of the cotton crop in India is harvested by handpicking, by women workers in general. Manual harvesting is very labour intensive and also a difficult activity involving drudgery. Cotton cultivation in India occupies a big share in commercial crops and is facing a major problem of harvesting labour. Objective of this work is to design and develop a cotton boll harvesting robot which is suitable for Indian farming practices meeting the needs of small and medium scale farmers. Field study and detailed literature review has been carried out to understand the cultivation of cotton crop, current harvesting practices and harvesting robots developed for other crops. Data collected through field visits was used to develop the cotton plant canopy and boll distribution within the canopy. This helped to decide the harvesting task space, maximum reach, and cotton-picking trajectories for the proposed cotton boll harvesting robot. Based in these requirements, specifications of the proposed cotton-picking robot were developed. Different conceptual robot designs involving standard arm configurations were developed to meet the specification and the best was selected considering compactness, weight, operational speed and control complexity. The selected design is a three link TRR configuration robot with mobile base equipped with vacuum type end-effector. A 3D model of the cotton boll harvesting robot was created using SolidWorks software and the model was simulated in ADAMS software to validate its working and extract joint torques and other results. Detailed design of components and sub- systems was carried out to meet the design requirements of cotton boll harvesting robot. Designed components were fabricated as per requirements, sub systems were integrated and assembled. The developed cotton boll harvesting robot was integrated with the controller, programmed and proved for its work successfully. The developed robot has been tested in controlled laboratory conditions and it is capable of harvesting cotton bolls, with an average time of 60 sec to pick 10 cotton bolls. The overall weight and cost of the system can be reduced further through optimization of sub-systems/ components. Also, future research has to focus on implementing image processing and testing of the robot in outdoor farming conditions. By replacing the dc motors used presently with servo motors, high precision and accuracy of the system can be achieved.
Keywords: automation, cotton picking, harvesting robot, manipulator, work volume

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1 Introduction

India is mainly an agricultural country; agriculture is the occupation for 60% of the population either directly or indirectly. Agriculture contributes about 16% of total GDP and 10% of total exports. Due to the gradual increase in population, the demand for food products is increasing but on the other side availability of labour for agricultural activity is continuously decreasing. For many crops, harvest labour accounts for as much as one-half to two-thirds of the total labour costs. Agricultural automation has become a major issue in recent years. Most of the efforts in this extensive research area

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have been devoted to fresh market fruit and vegetable harvesting tasks, which are generally, time consuming, tiring, and particularly demanding (Gebre et al., 2016). Robotic harvesting offers an attractive potential solution for reducing labour costs while enabling more regular and selective harvesting, optimizing crop quality and increasing profit (Nagarjun et al., 2020; M M Ullegaddi et al., 2021; Mehta and Burks, 2014; Yoshikawa, 1985; Sarig, 1993).

2 Problem statement

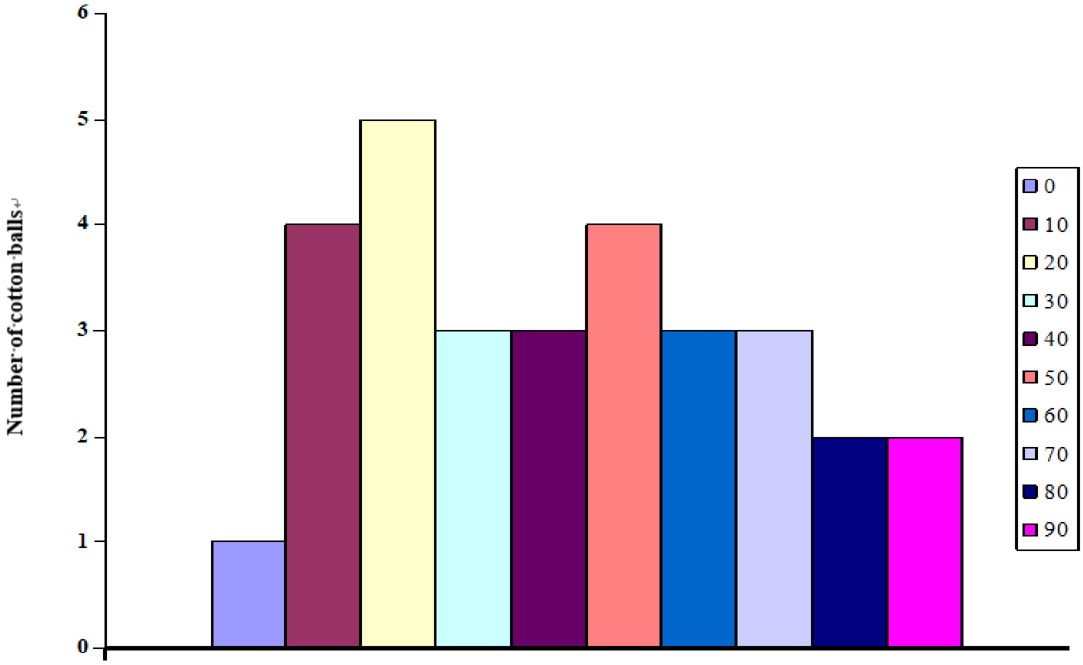
Cotton crop is a very important commodity in Indian agriculture and it has played a major role in economy of the country. In India agriculture is facing serious challenges like scarcity of agricultural labour, not only in peak working seasons but also in normal time. This is mainly for increased non - farm job opportunities having higher wages and low status of agricultural labours in the society. Replacing the traditional agricultural practices with the mechanization will help in improving the output. Considering the case of cotton harvesting, picking of cotton bolls with high precision is important to increase the rate of productivity (Chateau et al., 2000). Manual picking is time consuming process, complex hand movement to reach every single boll in the plant. Hence present work is aimed to reduce the manual effort in cotton picking and to increase the efficiency of the operation by developing compact and low-cost robotic manipulator for harvesting cotton bolls (Zion et al., 2014; Lehnert et al., 2017; Bulanon and Kataoka, 2010; Van Henten et al., 2002; Juste and Sevila, 1991, Ullegaddi, M. M., R. Shashank. 2021).

3 Design of the robot for harvesting cotton bolls

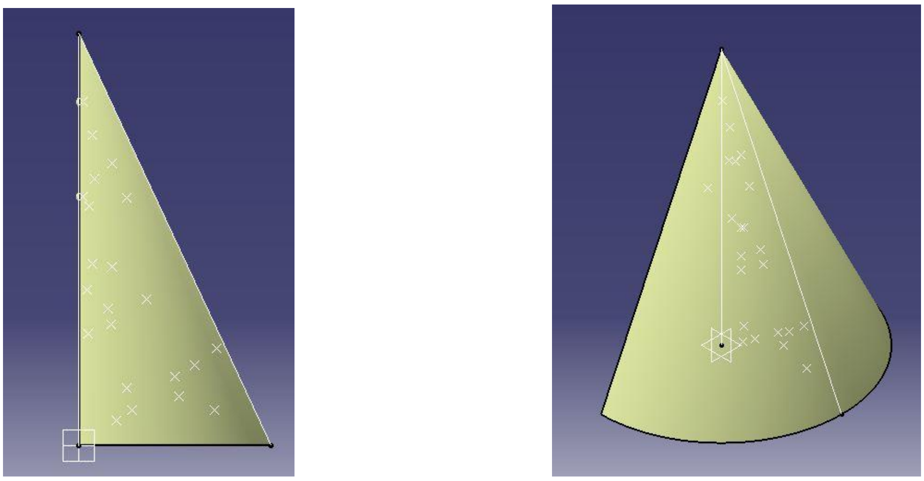
In order to develop the specifications for proposed cotton boll harvesting robot, field visit and interaction with farmers who are involved in cotton crop cultivation was carried out at the location Belgaum is located at 15.87°N 74.5°E. Detailed in subsequent sections. From the field study and interaction with farmers, the important data such as row spacing, plant to plant spacing, height of the plant, number of bolls per plant, location of the cotton boll etc. has been gathered. In Figure 1 cotton canopy is shown.

Figure 1 Cotton crop-field visit

The variations of the plant height and distribution of bolls are the constraints that need to be considered while developing and designing the robot for harvesting cotton bolls. In Figure 2 information about the distribution of cotton boll with respect to plant height is collected and work space of the cotton plant is shown.



Plant Height (In cm)



Side View Isometric View

Figure 2 Distribution of bolls in Bollguard II cotton variety

Based on the gathered information, basic specifications of the robot are developed. Specifications of the cotton boll harvesting robot are tabulated in Table 1.

Table 1 Specifications of harvesting robot

S. No	Parameter	Specifications	Unit
1	Ground clearance	100	Mm
2	Distance between wheels	400	Mm
3	Drives	Electric DC drives	----
4	Operating speed	25	mm s^{-1}
5	End effector	Vacuum type	----

3.1 Concept generation and evaluation

From existing harvesting robots for other crops and manual method of harvesting it can be observed that still the developed harvesting robots are not suitable for small scale farmers because of their complexity and cost (Sistler, 1987; Belforte et al., 2006; Pons et al., 2006). To overcome all the drawbacks of manual harvesting operation automation is the alternate solution. By automating the harvesting operation productivity of the cotton crop can be increased. To address the identified specifications, the most suitable cotton boll harvesting robot concepts are developed. Concepts are shown in Figures 3, 4, and 5.

Concept 1: Robot mechanical structure consists of three DOF (Degrees of Freedom) and it is driven by DC (Direct Current) geared motor. This mechanism consists of TRR (Translation, Rotation & Rotation) as shown in Figure 3 which helps in covering complete canopy of the cotton plant. Mechanism is simple, compact, and lightweight, less implementation difficulty and cost-effective design. The controlling of the harvesting robot mechanism can be accomplished by using toggle switches or it can be controlled using RF controllers (Van Henten et al., 2009; Sandini et al., 1990; Monta et al., 1995).

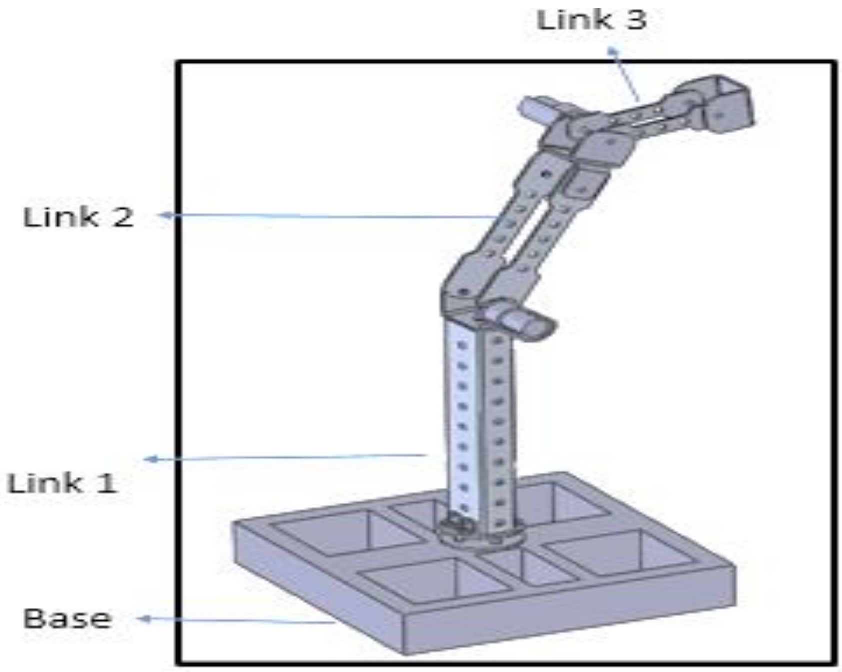


Figure 3 TRR (Translation, Rotation & Rotation) robotic manipulator

Concept 2: In this concept prismatic joint is used for the second joint. To actuate prismatic joints a greater number of components such as rack and pinion, solenoid mechanisms are required. Due to increase in number of components and sub-assembly robot is less compact, high weight, less cost-effective design and involves complexity in controlling. As shown in Figure 4 (Wang et al., 2008).

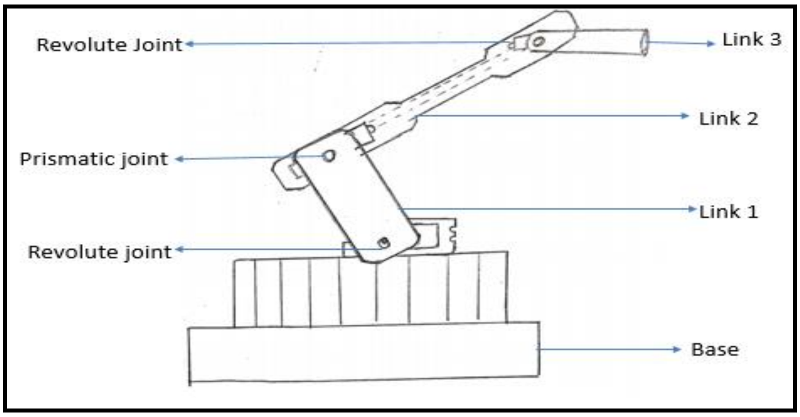


Figure 4 RPR (Rotation, Prismatic & Ration) robotic configuration

Concept 3: In this concept vacuum type end effector is attached to the third link of the robotic system. System produces noise, difficult to control, provides very low power to weight ratio, require air pressure. It is more suitable for pick and place applications as shown in Figure 5 (Bontsema et al., 2014; Ceres et al., 1998).

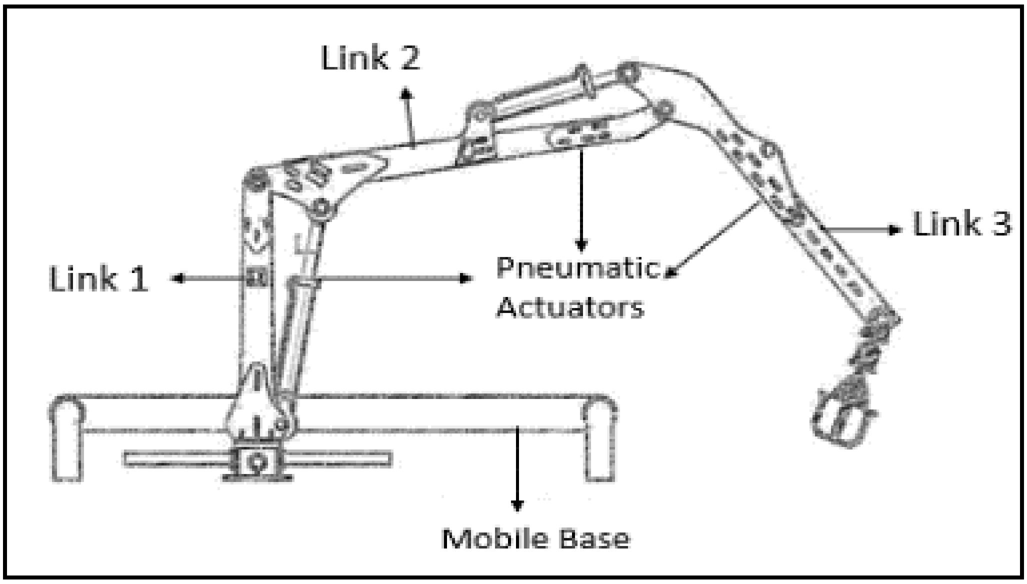


Figure 5 RRR (Rotation, Rotation & Rotation) robotic manipulator

3.2 Evaluation of concepts

Table 2 Comparison of concepts

Sl. No	Advantage	Limitation
Concept - 1	Less mechanical complexity Provides high strength and stiffness Mechanism facilitates maximum area coverage & high productivity	High precision in fabrication is required
Concept - 2	Electrical drives are used for actuation Capable of covering complete canopy of the cotton plant	High mechanical complexity in fabrication Less compact and High power consumption
Concept – 3	System is suitable for working in any environmental condition Suitable for pick and place applications	Complexity in programming and controlling the robot Less power to weight ratio

All the three concepts are considered and the best concept is selected on the basis of advantages and limitations listed in Table 2. As such concept 1 is suitable for harvesting the cotton bolls.

3.3 Development of CAD model of finalized concept

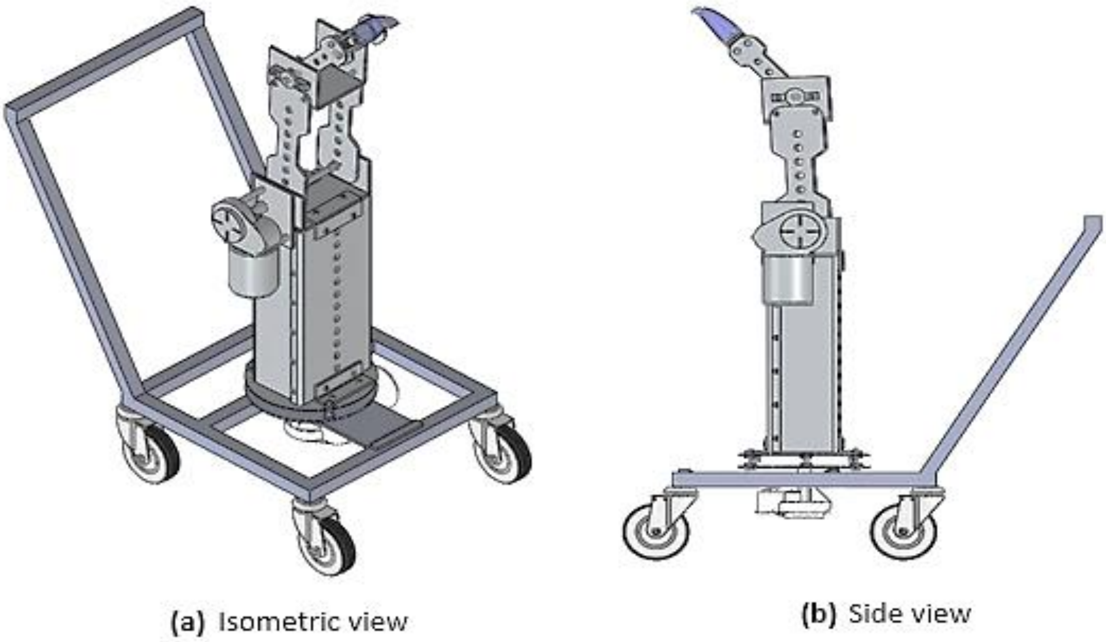


Figure 6 Cotton boll harvesting robot

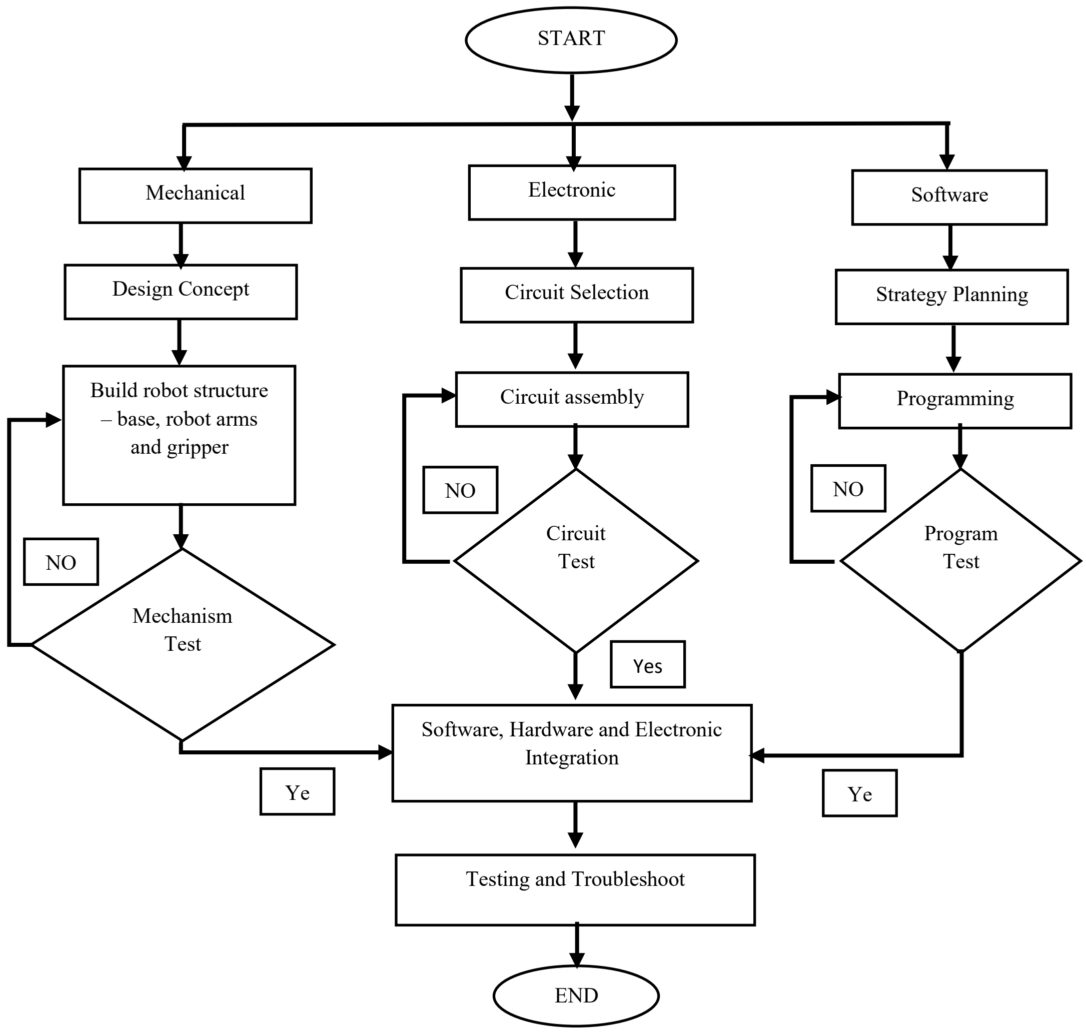


Figure 7 Flowchart for the development of cotton boll harvesting robot

4 Design of sub-system of robot

The system includes mainly three different sub – mechanical structure, electronic integration and controller circuit as shown in Figure 7.

4.1 Spatial transformation

A spatial transformation defines a geometric relationship between each part of the system. In this case cotton boll harvesting robot base link is related to the vacuum type end effector. Transform *{T}* describes the end effector location relative to the base frame *{B}*.

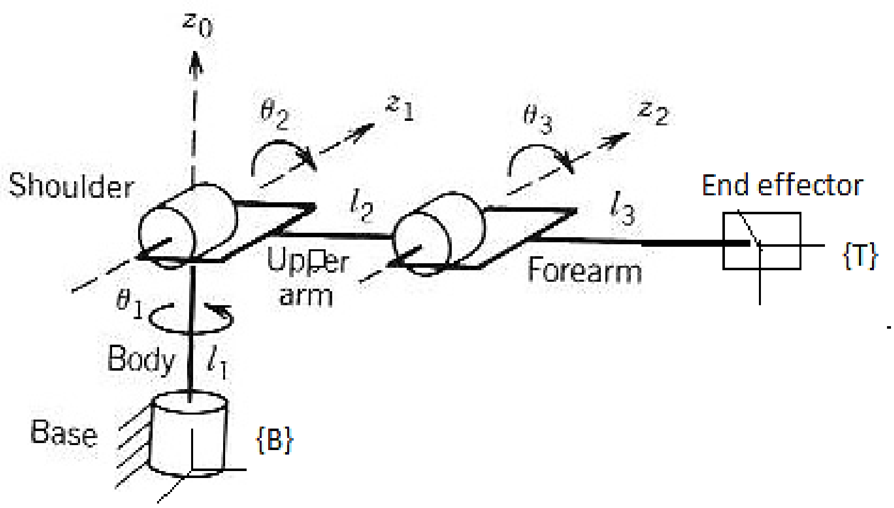


Figure 8 Structure of TRR robotic configuration

$$T = \begin{matrix} C1*C23 & -c1*S23 & S1 & C1\,(a3*C23+a2C2) \\ S1*C23 & -S1*C23 & -C1 & S1(a3*C23+a2C2) \\ S23 & C23 & 0 & a3*S23 + a2s2 \end{matrix}$$

C – Represents Cos function of the joint angle

S – Represents Sine function of the joint angle

4.2 D-H parameters

Cotton boll harvesting robot can be described kinematic ally by giving the values of four quantities for each link. Two parameters (link length and link twist) describe the link itself and other two parameters (link offset and joint angle) describe the link connection to a neighbouring link. D - H parameters of cotton harvesting robot are listed in Table 3.

Table 3 D-H parameters of cotton harvesting robot

Joint	Joint angle	Link length	Link offset	Twist angle
	θ (degrees)	a (cm)	d	α (degrees)
1	θ_1	0	35	90
2	θ_2	25	0	0
3	θ_3	25	0	0

4.3 Manipulator kinematics

Inverse kinematics: Determined the joint parameters relative to the known end effector location. Transformation of orientation and position of end effector from Cartesian space to a joint space. In harvesting robot application, the location of cotton bolls is known and the joint parameters are determined using inverse kinematics as shown in Figure 9.

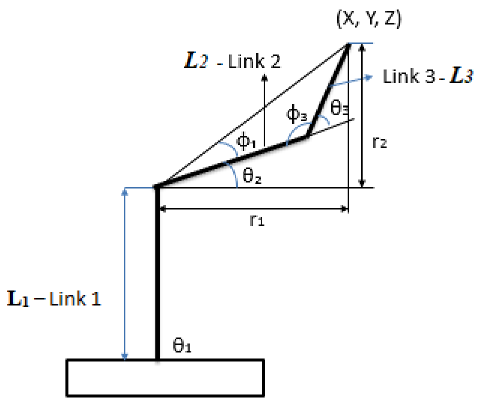


Figure 9 Schematic representation of TRR robot

From Figure 9,

$\theta_1 = \arctan\left(\frac{Y}{X}\right)$, $\theta_2 = \phi_2 - \phi_1$, $r_2 = Z - L_1$, $r_1 = \sqrt{X^2 + Y^2}$, $\phi_2 = \arctan\left(\frac{r_2}{r_1}\right)$, Applying cosine law,

$(L_3)^2 = L_2^2 + r_3^2 - 2 L_2 r_3 \cos(\phi_1)$,

Where,

L_1 – length of link 1

L_2 - length of link 2

L - length of link 3

$\phi_1 = \text{arc cos}\left(\frac{L_3^2 - L_2^2 - r_3^2}{-2 L^2 r_3}\right)$,

$r_3 = \sqrt{r1^2 + r2^2}$ $\phi_3 = \text{arc cos}\left(\frac{r_3^2 - L_2^2 - L_3^2}{-2 \times L_2 \times L_3}\right)$,

$\theta_3 = 180 - \phi_3$

4.4 Static force analysis

Newton's first law applied to all links that are at rest or moving at constant velocity, for an object to be in static equilibrium the following two necessary conditions must be met.

Condition 1: The combination, or resultant, of all external forces acting on the object is equivalent to zero and does not cause it to translate ($\sum F = 0$).

Condition 2: The moment due to any external force is cancelled by the moments of the other forces acting on the object and do not cause it to rotate about any point ($\sum M = 0$).

It is assumed that the robot arm is not subjected to any forces relating to tasks or payloads at the tip of link 3. Therefore, the only forces exerted are those needed to overcome gravity. Equilibrium with reaction forces and joint torques must be established. Figure 10 displays the free body diagrams for the three links of the jointed manipulator structure.

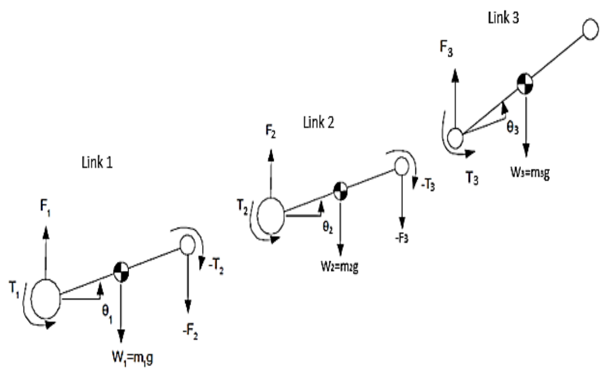


Figure 10 Free body diagram of individual links

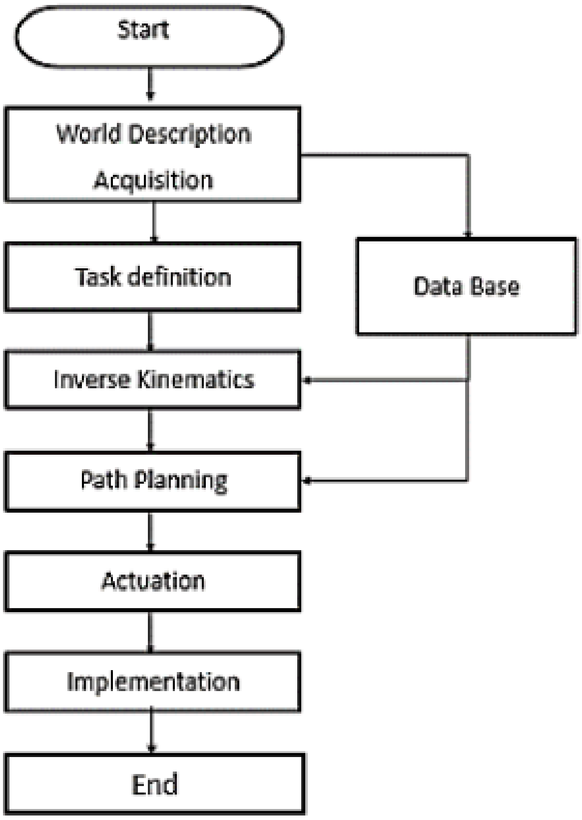


Figure 11 Flow chart of Control System

Static forces in a manipulator, all the joints are considered as locked so that the manipulator becomes a structure. The magnitude of these forces are,

F3 = (m3 × g) (1)

F2 = (F3+m2 × g) (2)

F1 = (F2+m1 × g) (3)

Torque acting at each joint,

Joint 3, T3 = (m3 x g x l3c cos (θ_1 + θ2+ θ3)), (4)

cos ($\theta_2+\theta_3$) + l_2 cos (θ_2)]),(5)

Joint 1, $T_1 = (W_1 \times l_1c \cos(\theta_1) + m_2 \times g\, [l_2c \cos(\theta_1 + \theta_2) + l_1 \cos(\theta_1)] + m_3 \times g\, [l_3c \cos(\theta_1 + \theta_2 + \theta_3) + l_2 \cos(\theta_1 + \theta_2) + l_1 \cos(\theta_1)])$ (6)

Where,

W1, W2, W3 – Weight of the each link

$\theta_1, \theta_2, \theta_3$ – Angle made by the links

4.5 Control system

A micro controller is an inexpensive single chip computer. For cotton harvesting robot renesas microcontroller is selected because it combines advanced low power technology, outstanding performance and broadest line up compared to other microcontrollers. Microcontroller consists of 3 sections for controlling the task of harvesting robot such as Control section, Power section and Communication section as shown in Figure 11.

4.6 Simulation of cotton boll harvesting robot

3D model of cotton boll harvesting robot is created using SolidWorks software and the model is simulated in ADAMS software. Forces and torques acting at each joint location is obtained using ADAMS simulation software. Simulation includes importing CAD model to the ADAMS VIEW. To establish connectivity suitable joints were created and provided actuation by assigning motion to the individual joints. Motion is provided through step function to calculate force and torque at the joints. Importing of CAD model and assigning joints is shown in Figure 12.

Figure 12 CAD model used in ADAMS

4.7 Prototype of robot for harvesting cotton bolls

After theoretical modelling and analysis, the next step integrated each of the components such that they work together in an efficient manner in order to collect cotton boll. Robotic system is divided into sub-assemblies for fabrication, it consists of some standard components and some of the components are fabricated based on the requirement. By systematically employing the engineering design principles, all the sub-systems required for the operation of intended cotton harvesting robot were designed. Considering the outcomes from the design of components/sub-systems, the parts were fabricated and assembled using standard manufacturing routes. Final model of the Cotton boll harvesting robot is shown in Figure 13 after complete assembly.

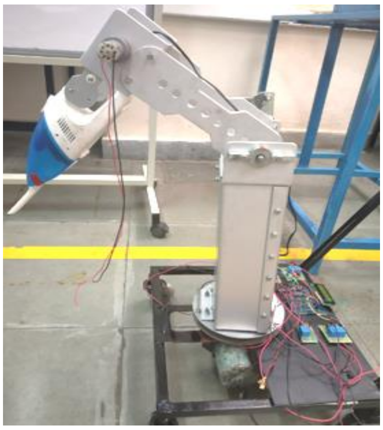


Figure 13 Cotton boll harvesting robot

5 Result and discussion

5.1 Manipulator kinematics

From field visit cotton boll location information was collected, to reach the target position joint angles calculated using inverse kinematics. Geometric method is selected for obtaining joint angles for each cotton boll location by decomposing the spatial geometry and the joint angles are listed in Table 4.

Table 4 Joint angle values for different cotton boll locations

Cotton Boll Location (*X,Y,Z*)	Joint 1, θ_1 (degree)	Joint 2, θ_2 (degree)	Joint 3, θ_3 (degree)
(8,26,85)	72.89	24.57	128.9
(15,24,72)	71.56	41.37	46.24
(14,20,58)	70.97	53.75	27.97
(10,22,48)	65.37	-23.35	-59.05

5.2 Static force analysis

Free body diagram of the 3-link jointed arm structure is obtained and calculated forces and torques acting at each joint for cotton boll locations (10, 22, 48) and they are listed in Table 5.

5.3 Simulation of harvesting robot

3D model of Cotton boll harvesting robot is created using SolidWorks software and the model is simulated in ADAMS software. Forces and torques acting at each joint location is obtained using ADAMS simulation software and they are listed in Table 6.

Table 5 Force and torque

	Joint 1	Joint 2	Joint 3
Force (N)	17.64	10.29	5.39
Torque (kg.cm)	119.04	71.68	38.69

Table 6 Force and torque acting at each joint for different boll location

Cotton Boll Location	F1 In N	F2 In N	F3 In N	T1 In Nm	T2 In Nm	T3 In Nm
8,26,85	16.9	12.8	6.2	12.0	8.4	4.0
15,24,72	15.8	11.6	5.5	11.5	8.3	3.8
14,20,58	14.5	11.5	4.5	10.1	7.5	3.6
10,22,48	17.6	10.2	5.3	11.6	7.0	3.8

6 Conclusion and future direction

To enhance the productivity of cotton crop, mechanization of important operations is essential. Harvesting is one of the important operations in cotton crop production. In order to mechanize the harvesting operation in cotton crop production, a low-cost cotton boll harvesting robot suitable for small farmers is indigenously developed in the present work.

Detailed specification of harvesting robot for cotton crop has been successfully developed based on the field study and literature review. To meet these specifications, three alternative concepts were developed and first concept was selected. The detailed design of sub-systems/components of the harvesting robot has been carried out. Complete fabrication of the robot has been successfully completed. The developed cotton boll harvesting robot is integrated with controller, programmed and demonstrated for its working successfully.

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