Development of mobile dual PR arm agricultural robot

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Abstract. New efficient and low-cost technology for planting and watering are needed for the growth of agriculture sector. This paper deals with the novel design, fabrication and control of a mobile dual Prismatic-Revolute (PR) arm agricultural robot which can be used by farmers and households for domestic cultivation. Proposed robot is a prototype of a low cost wheeled robotic system which consists of four main subsystems such as digging module, seed module, moisture sensor-based watering module and inline motion module. This work also includes the kinematic, static and dynamic analysis of the robotic system. Time history plots of dual arm mechanism and results of static & dynamic analysis are presented. Farming experimentation is carried out using the prototype and results are analysed. This dual PR arm agricultural robot is a good, economical solution for agricultural problem of farmers and can also be used for domestic cultivation.

1. Introduction

Agriculture is the main source of income in India. One of the main challenges in agriculture is the shortage of labour. Countries such as Japan, USA, China, and Korea etc. already started robot-based farming. In India robot-based farming is still in its initial stages. One of the main issues in the implementation of robot farming is the high initial investment and maintenance. In near future, India will also promote robot farming because of the lack of farmers. If the robot is completely automated, this could reduce the labour and cost, increasing the productivity of crops and vegetables. Development of such type of robots at lower cost is a challenging task. Important literatures reviewed related to the dual PR arm agricultural robot for identifying the research gap. Astrand and Baerveldt [1] developed a vision based mobile robot for weed control at outdoor agricultural land. In this paper, a weed removal tool removes the weeds along the row of crops after the image is analysed. High cost camera and subsystems are used for the implementation. Zhang et al. [2] introduced a GPS based mechanized and site-specific farming using autonomous agricultural vehicles for meeting the demands of precision agriculture. Luis et al. [3] tried to develop a pattern for fleet robots to improve reliability, decrease complexity, and permit the integration of various functions related to farming. Yael Edan [4] proposed a concept for a field robot for selective harvesting of easily bruised fruit and vegetables with the help of a Cartesian robotic manipulator. Sunitha et al. [5] developed a self-navigating ploughing and seed sowing robot which uses an image sensing system. Neha et al. [6] presented a detailed review on agriculture robot technologies including innovative strategies and machines. Tejaswani et al. [7] introduced a semi-automatic robotic system with multiple capabilities such as seeding, ploughing and
waste plant cutting. Android application is used to provide the input to this robot. Devesh et al. [8] focused on the design of agricultural robot for water spraying, seeding and cutting operation. It is clear from the literature that the available robots are costlier and are not effective in digging, seeding, covering and watering. Robots which are suited for both households and medium scale applications are not reported anywhere in the literature. This paper proposes the development of a robot which can be used by farmers and households for cultivation. This work also includes the kinematic, static and dynamic analysis of the Agricultural robot. This model is a low cost wheeled robotic system which consists of 4 main subsystems such as digging module, seed planting module, watering module and inline motion module. The proposed robot is economically suitable for all agricultural problem faced by farmers and is also suitable for cultivation of homemade vegetable and plants. This paper also presents the seeding experimentation using wheeled robot in a flat terrain agricultural land.

2. Modelling of robot

The robot is designed, fabricated and tested in real time in completely automated mode. Kinematic analysis is done using Denavit Hartenberg (D-H) parameters [9]. Static structural analysis is carried out by using ANSYS package and the dynamic modelling is done using Langrangian formulation. Assembled view of the robot model and internal parts are given in figure 1. Sub systems of robot are designed, fabricated and assembled for experimentation. The wheels of the dual Prismatic-Revolute (PR) arm agricultural robot are steered using dc motors. When the robot reaches the desired position, robot digs the hole, plants a seed and covers the soil above it, using the digging and covering dual arm module. Then it waters the seeds using watering module based on the moisture content in the soil, detected by soil moisture sensor. Moisture sensor send the signal to the controller which in turn gives the signal to the pump to "on or off", based on the level of water content in the soil. The distance between each seeding position is measured in each row using encoder based inline motion module. After completing the process, the robot moves to the next position and repeats the same. When the row is completed the robot turns and start a new row, similarly the whole field area will be covered. A simple algorithm is used for the rough estimation of distance between seeds.

2.1 Working modules of robot

The digging module used in the mobile robot is a PR manipulator. The prismatic motion is used to move the end effector up and down and the end effector is rotated to perform the digging task. The soil covering module is also a PR manipulator and the prismatic motion is inclined to the horizontal which moves the end effector up and down. The end effector is rotated to perform the soil covering operation. The digging and soil covering task is completely carried out by using a dual PR robotic manipulator. The dual PR robotic manipulators are kinematically synthesized on the basis of the Denavit-Hartenberg (DH) modelling. Dimensions of robot are given in the table 1.
Table 1 Dimensions of dual PR arm agricultural robot

| Base dimensions | Max. reach of soil digging arm | Max. reach of soil covering arm |
|-----------------|-------------------------------|--------------------------------|
| 0.35m×0.25m with height of 0.2m | 0.06m                         | 0.05m                          |

2.2 Kinematic, Static and Dynamic Modelling of Robot

Frames are assigned and final pose matrices are determined using DH parameters. Dual arm (PR soil digger and soil covering mechanism) and mobile base with frame assignments are given in figures 2(a), 2(b) & 3. DH parameters of PR soil digger and soil covering modules are given in tables 2 and 3 respectively. Final transformation matrices for dual arm and base are given in equations 1, 2 & 3.

- **Table 2 DH parameters of Soil digging arm**

| Joint | \( \theta_{n+1} \) | \( d_{n+1} \) | \( a_{n+1} \) | \( \alpha_{n+1} \) |
|-------|-------------------|--------------|--------------|-----------------|
| 1     | 0                 | \( d_1 \)    | \( k \)      | 0               |
| 2     | \( \theta_2 \)    | \( p \)      | 0            | 0               |

\[
T_2^0 = \begin{bmatrix}
C2 & -S2 & 0 & k \\
S2 & C2 & 0 & 0 \\
0  & 0  & 1 & P + d_1 \\
0  & 0  & 0 & 1 \\
\end{bmatrix}
\]  

(1)

- **Table 3 DH parameters of Soil covering arm**

| Joint | \( \theta_{n+1} \) | \( d_{n+1} \) | \( a_{n+1} \) | \( \alpha_{n+1} \) |
|-------|-------------------|--------------|--------------|-----------------|
| 1     | 0                 | \( d_2 \)    | 0            | -\( \pi/3 \)    |
| 2     | \( \theta_2 \)    | \( h \)     | 0            | 0               |

Figure 2 Kinematic models of the PR arms
(a) soil digging arm;
(b) soil covering arm.
\[
T_2^0 = \begin{bmatrix}
C2 & -S2 & 0 & 0 \\
0.5S2 & 0.5C2 & 0.866 & 0.866h \\
-0.866S2 & -0.866C2 & 0.5 & 0.5h + d_z \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (2)

Kinematic analysis helped in the dimensional synthesis of dual arm and the base. Inverse kinematic solutions of arms are determined directly from the equations 1 & 2 by equating with required pose matrices.

![Figure 3](image3.png)

**Figure 3** Kinematic modelling of the mobile base (2 DOF)

One main part of the digger arm on which maximum load acting is the flange. Static analysis of the flange is carried out and thickness is determined based on stress and deflection. This analysis is carried out using ANSYS R15.0 academic software. Complete static analysis details are given in the result section. Dynamic analysis of the dual arm is carried out for the selection of actuators based on the joint torque. Torque at each joint of the dual arm is calculated by using Lagrangian-Euler formulation [9, 10].

![Figure 4](image4.png)

**Figure 4** Dual arm: Variables selected for dynamic modelling
(a) Soil digger;
(b) Soil covering module.
Dynamic model of a 2 DOF soil digging and covering modules are formed by using Lagrangian – Euler formulation. As per this theory, 

Joint torque or force: 

$$\tau = \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}} \right) - \frac{\partial L}{\partial q}$$  \hspace{1cm} (4)

Where \(q\) is the joint variable and \(L\) is the Lagrangian.

$$L = \text{Total Kinetic Energy} - \text{Total Potential energy} = \sum K_i - \sum P_i$$  \hspace{1cm} (5)

Dynamic model of a 2 DOF soil digger is determined as depicted below. The Lagrangian for PR soil digger:

$$L = \frac{1}{2} m_{d1} \ddot{d}_1^2 + \frac{1}{2} m_{d2} \ddot{d}_1^2 + \frac{1}{2} m_{d2} r^2 \dot{\theta}_2^2 + \frac{1}{2} I_{d2} \dot{\theta}_2^2 - m_{d1} g d_1 - m_{d2} g d_1 - m_{d2} g h$$  \hspace{1cm} (6)

Where, \(m_{d1}\) and \(m_{d2}\) are the masses of the first and second link of the soil digging arm respectively.

Consider the first prismatic joint of the soil digger for the determination of joint force. Using the Lagrangian formulation:

$$f_d = \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{d}_1} \right) - \frac{\partial L}{\partial d_1}$$  \hspace{1cm} (7)

On substitution in equation (7), Prismatic joint force of soil digger \((f_d)\) is:

$$f_d = (m_{d1} + m_{d2}) \ddot{d}_1 + m_{d1} g + m_{d2} g$$  \hspace{1cm} (8)

Torque at the second joint of the soil digger \((\tau_d)\) is:

$$\tau_d = \left( \frac{\partial L}{\partial \dot{\theta}_2} \right) - \left( \frac{\partial L}{\partial \theta_2} \right)$$  \hspace{1cm} (9)

ie, \(\tau_d = m_{d2} r \dot{\theta}_2 + I_{d2} \ddot{\theta}_2 = (m_{d2} \dot{r}^2 + I_{d2}) \ddot{\theta}_2 \)  \hspace{1cm} (10)

Similarly for the second PR soil covering arm, Lagrangian:

$$L = \frac{1}{2} m_{c1} \left( \ddot{d}_2^2 \right) + \frac{1}{2} m_{c2} \ddot{d}_2^2 + \frac{1}{2} m_{c2} r^2 \dot{\theta}_2^2 + \frac{1}{2} I_{c2} \dot{\theta}_2^2 - m_{c1} g (d_2 \sin \alpha) - m_{c2} g (d_2 \sin \alpha + h)$$  \hspace{1cm} (11)

Where, \(m_{c1}\) and \(m_{c2}\) are the masses of the first and second link of the soil covering arm respectively.

First joint force \((f_c)\) and second joint torque \((\tau_c)\) of soil covering arm are given in equation (12) & (13) respectively.

$$f_c = (m_{c1} + m_{c2}) \ddot{d}_2 + m_{c1} \sin(\alpha) g + m_{c2} \sin(\alpha) g$$  \hspace{1cm} (12)

$$\tau_c = (m_{c2} \dot{r}^2 + I_{c2}) \ddot{\theta}_2$$  \hspace{1cm} (13)

2.3 Seed Feeding Module

Seed feeding module consists of a seed storage elevated container with a passage at the bottom and an intermittent seed feeding mechanism. Seed feeding module is a novel mechanism proposed for seed sowing, which is given in figure 5.
A soil moisture sensor is attached to the digger which senses the moisture content in the soil, if the soil is having less moisture content, it will trigger the water pump and the required amount of water is pumped after completing the farming process. Proposed farming robot can also be used for spraying organic pesticides.

3. Fabrication and control of robot

Electronic circuit for the control of the robot with data flow is given in figure 6. There are seven motors, in which two are used for mobile base actuation, four are used for soil digger and soil covering module and one small servo is used for operating seed feeding valve. A pump is operated based on the moisture sensor data.

Proposed robot can be used for inline and non-parallel/nonlinear farming operations. The methodology of inline seed sowing operation is explained with the help of figures 7 & 8. Intermediate ‘n’ set points in each line for sowing are given in figure 7. Robot moves towards the respective set position with respect to the inertial frame based on the input signal. Operations such as soil digging, covering and
watering operations are carried out at the first set position before moving to the second set point location. The same procedure is repeated for ‘n’ set points and then moves to the next row and so on.

Figure 7 Robot motion: Straight line path

Robot farming procedure and control algorithm are given in detail in the flow chart shown in figure 8. Assembled robot is given in figure 9(a). Ten set points are selected in one line during the experimentation using the prototype of dual arm farming robot.

Figure 8 Robot farming algorithm
4. Results and discussion

Robot is designed based on kinematic, static and dynamic analysis. Workspace analysis helped for the selection of dimensions of dual arm. Static structural analysis is performed for the determination of thickness of the flange. Material selected for the analysis is C17 mild steel. Yield strength, ultimate tensile strength and density of this material are 247MPa, 841MPa and 0.00758kgm/cc respectively. Load applied during the structural analysis is taken as 25N. Maximum induced stress and deflection obtained after the analysis are 52.65MPa and 0.00356 mm respectively. Images of deformed flange at loading conditions are given in figure 10(a) & 10(b) respectively. Induced stress is much less than the yield strength of the material with an assumed safety factor of 2. Hence, selected dimensions are safe and the optimum thickness of the flange of soil digger is 2 mm.

![Figure 9 Mobile dual PR arm agricultural robot](image)
(a) Assembled robot for testing; (b) Final prototype of the farming robot.

![Figure 10 Static analysis of the PR arms](image)
(a) stress analysis; (b) deflection.
Time history plots of soil digger and soil covering arms are shown in figure 11 and figure 12 respectively. It is assumed that joint variables for the prismatic and revolute joints are varying as cubic smooth function for achieving the smooth motion for arms. Position, velocity and acceleration variations are smooth for soil digger and covering arms as expected and hence minimize the jerk. Maximum possible mobile robot base velocity is 0.78m/s with the rated wheel speed of 100rpm. Mobile base is moving with constant velocity between the seed sowing set points.

![Figure 11](image1.png)

**Figure 11** Position, velocity and acceleration of soil digger arm
(a) First joint;
(b) Second joint.

![Figure 12](image2.png)

**Figure 12** Position, velocity and acceleration of soil covering arm
(a) First joint;
(b) Second joint.

Torque at various joints of digging and covering arms are as shown in figure 13. Actuators are selected based on actual torque values using the motor data sheet. It is clear from the plots that the maximum torque values required to get the prismatic motion of digger and covering arms are 0.08Nm and arms

![Figure 13](image3.png)

**Figure 13** Joint torques
(a) soil digger arm;
(b) Soil covering arm.
0.04Nm respectively. Similarly maximum torque values at second joint of digger and covering are 0.014Nm and 0.025Nm respectively. Actual torque is approximately 4 times the theoretical torque obtained from plots. Safety factor is assumed as 4 because the soil resistance is not considered in the modelling. Prototype used for the farming is as shown in figure 9(b). Robot has been working perfectly for farming and watering.

5. Conclusions and outlook
Farming experimentation is carried out for ten set points in straight line on the flat terrain. All the working modules are tested during experimentation. Plantation in the provided field is carried out in a required sequence and pattern by using this robot. Distances between seeding set points can be changed according to the type of plants. Distance between seeding set points is taken as 1m for ladies finger plant during the experimentation given in this paper. The digging space required for this seed is 0.035×0.035m×0.035m. The tool can be changed based on the type of plant for the required digging space. Ten set point experiments are carried out in a straight line with a constant distance of 1m between the start and end points. The positional error in ten set points farming experiments was approximately from ±3% to ± 5%. Average time required for farming one set position was 76s instead of an expected average time of 60s. This variation is due to the irregularities of terrain and slipping. The robot moves in a straight-line path through a specified path using an inline encoder module. Proposed robot can be used in land with different terrains by changing the base wheel assembly. Hence, Present wheeled system can be changed to tracked wheel for achieving the mobility on various modes of terrains. Torque/force plots at various joints of digging and covering modules are plotted and actuators are selected based on this plot. Proposed robot mainly focuses on the domestic cultivation of vegetables and pulses. IOT based farming can also be incorporated in this automated robot for farming in vast area of land through intelligent farming.

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