Design of an All-Purpose Terrace Farming Robot

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Abstract—Automation in farming processes is a growing field of research in both academia and industries. A considerable amount of work has been put into this field to develop systems robust enough for farming. Terrace farming, in particular, provides a varying set of challenges, including reliable step climbing methods and stable navigation in unstructured terrains. We propose the design of a novel autonomous terrace farming robot, ‘Aarohi’, that can effectively climb steep terraces of considerable heights. The design optimisation strategy for the overall mechanical structure is elucidated. Further, the embedded and software architecture are presented for a working prototype. The navigation strategy for autonomous traversal over the terrace steps using the scissor lift mechanism has also been discussed along with the experimental results for the controller. The adaptability of the design to specific operational requirements and modular farm tools allow ‘Aarohi’ to be customised for a wide variety of use cases.

Index Terms—Agricultural automation, Step climbing, Terrace farming

I. INTRODUCTION

Global food demand is expected to increase anywhere between 59% to 98% by 2050 [1]. To meet such demands, revolutionising the field of agriculture with mechatronic solutions can be crucial as discussed in [2]. On steep slopes, terrace farming is one of the most efficient ways of conserving soil and water [3]. Automation in this field will pave the way for larger crop yield and productivity. As evident in prior work [4], automation is feasible outside the domain of large scale farming and can be useful in smaller scales as well. However, there are multiple challenges in automating the process of terrace farming. The use of petrol or diesel tractors is non-viable due to the narrow size of steps [5]. As a result, most of the farmers rely on the use of traditional hand tools [6] [7].

Full-scale development and commercialisation of a terrace farming robot is inherently a challenging task. Firstly, it requires the robot to be able to traverse long and curved terraces on hilly slopes. These terraces are typically 60-80 m long with varying widths along the length, which in turn requires the farm robot to be as compact as possible. Therefore a compact climbing mechanism is required which can efficiently climb up the step heights that can easily reach up to 40 cm. Moreover, the mechanism should also not rely on side wall friction as it is unavailable in soil. We reviewed several step-climbing mechanisms proposed by researchers and engineers to date. Broadly, various step-climbing robots can be put into either of these categories: (a) Wheeled robots, (b) Tracked or rail-based robots and (c) Legged robots. Wheeled step-climbing robots typically use multiple wheels in combination to roll, crawl and climb steps [8]. MSRox [9], one such wheeled robot, showed good adaptability on rugged terrain and steps. However, it requires that the radius of the star wheel subassembly be significantly greater than the step height, rendering it impractical for larger step heights. Tracked robots are also a popular choice for step-climbing as they have been found to work well for rough terrains [10], [11], but their reliance on side wall friction which maybe unavailable on the steps in terrace farms. Humanoids, such as HONDA ASIMO [12], NAO [13], and HRP-2 [14], have demonstrated capability for step climbing but they are extremely expensive and arduous to put into farming use. On the other hand, legged robots such as RHex [15] could be augmented with farming tools easily but the unstable chassis motion discourages their use for farming applications that require high precision and accuracy. Zhang et al. proposed another notable mechanism in Ref. [16], that combined lift or drop motion with the telescopic linear motion to achieve step climbing. However, the long telescopic mechanism not only restricted its quick turning capability but also caused imbalance of the entire robot in certain configurations.

As the existing mechanical designs of step climbing robots can not be directly put to use for automating terrace farming, we propose ‘Aarohi’, an autonomous terrace farming robot which consists of: 1) Novel scissor lift based mechanism for step climbing to handle steep terrace steps without using side wall friction, 2) Re-configurable and extendable chassis design for attaching different agricultural tools of varying sizes,
II. MECHANICAL DESIGN

In this section, we discuss the overall philosophy and design optimization of the mechanical structure of the robot. We focus on the design of our novel step climbing mechanism that facilitates the robot to traverse across steps with varying heights, seen in terrace farming. The scissor lift mechanism allows the robot to climb up and down the step. It also facilitates variable height adjustment during watering, pesticide spraying, and harvesting, so that these farming operations can be applied to a crop at different stages of growth and varying crop heights. Only two pairs of scissors are used in the prototype developed. However, multiple pairs of scissors could be used for climbing as shown in Fig. 3 depending upon the dimensions and weight of the farming tools required for specific use cases. In the prototype, the pair of front wheels and rear wheels are attached to one scissor lift mechanism each. The scissor-lift mechanism, which is considered as one of the most stable mechanisms for lifting actions in industries, has been used instead of fork-lift or lead-screw for lifting the robot because of the relative easiness in manufacturing, assembling and implementing. The two scissor lift mechanisms in the prototype are differentially actuated to climb up and down the stairs. To support the robot while climbing, four pairs of dummy wheels are used – one ahead of the front wheel, two between the front and rear wheels and one behind the rear wheels. Scissors units connecting the front and rear pair of wheels are attached with one linear actuator each to support the lifting of the robot. To ensure the prismatic vertical lift motion, guide rails are further attached to the scissor mechanism.

A. Design Optimization for Step Climbing Mechanism

When designing a scissor-lift mechanism, the location of the linear actuator’s attachment is critical because it directly impacts the mechanical advantage, the velocity ratio and high resultant stroke length \((h)\), and thereby influencing the choice of the linear actuator to actuate the system, and hence, the overall cost. In short, the position variables of the linear actuator attachment affect the force output and the stroke length of the actuator. The aim of the optimization is to achieve larger height of the scissor lift mechanism and also have a higher velocity. There are other design parameters such as the link lengths, link thickness, number of scissors, etc. that directly influence the force output and the stroke length of the actuator. Before picking an ideal set of position variables, it is necessary to establish equations for force output and the stroke

| Parameter | Description |
|-----------|-------------|
| \(n\)    | Number of scissor levels |
| \(\theta\) | Acute angle made by a link with x-axis |
| \(D\)    | Length of the scissor-link |
| \(h\)    | Height of the scissor lift mechanism in current configuration |
| \(H\)    | Height of the step |
| \(l\)    | Length of the actuator AB |
| \(S\)    | Stroke length of the linear actuator |
| \(i\)    | Number of scissors below the point B |
| \(a\)    | Fractional number between \((0, 0.5)\) \(aD\) denotes the length PA |
| \(b\)    | Fractional number between \((0, 0.5)\) \(bD\) denotes the length OB |
| \(F\)    | Linear actuator force required to actuate the scissor-lift at current configuration |
| \(L\)    | Load lifted by the scissor-lift, incorporating both robot and scissor-lift weight |
| \(t\)    | Thickness of the scissor-link |
length of a linear actuator in terms of the scissor-lift position variables. Without loss of generality, we can consider a $n$ stage scissor-lift mechanism as shown in Fig. 4. The linear actuator has one end static and the other translating. The translating end is attached to a point on a positively sloping link in the scissors (point A in Fig. 4) and the static end is attached to a fixed support (point B in Fig. 4). Point A is where the force is applied. When the translating end of the actuator extends, it will cause the scissor-lift to extend and vice versa.

In Fig. 4, O is the origin and XY is the reference coordinate axes for the analysis. The symbols used and their corresponding descriptions are tabulated in Table I.

$a$, $b$, $\theta$ and $n$ are the independent variables. $D$ and $i$ are assumed to be constant in our analysis. $i$ is set equal to $n-1$. The expressions $h$, $l$ and $F$, derived in Ref. [17], in terms of the independent variables, are shown in Eq. (1), (2), and (3), respectively. The stroke length of the linear actuator can be obtained by subtracting the length of the actuator in the maximum extended state and the maximum compressed state as expressed in Eq. (5). It is also required to find out the maximum force required to actuate the scissor-lift to choose the linear actuator. The force required to actuate the scissor-lift will be maximum when the scissors are in the most compressed state, i.e., when $\theta = \theta_{\text{min}}$. The maximum force, $F_{\text{max}}$, can be expressed as in Eq. (4).

\[
h = nD\sin\theta \tag{1}
\]

\[
l = D \left[ \lambda \cos^2 \theta - 2b\cos \theta + b^2 + (i + a)^2 \right] \frac{1}{2} \tag{2}
\]

\[
F = nL \left[ \frac{\lambda \cos^2 \theta - 2b\cos \theta + b^2 + (i + a)^2}{(b\cos \theta - \lambda \sin \theta)^2} \right] \frac{1}{2} \tag{3}
\]

\[
F_{\text{max}} = F \bigg|_{\theta = \theta_{\text{min}}} \tag{4}
\]

\[
S = l \bigg|_{\theta = \theta_{\text{max}}} - l \bigg|_{\theta = \theta_{\text{min}}} \tag{5}
\]

Where $\lambda = (\pi^2 - (i + a)^2)$ and $\lambda = 1 - a$. Clearly, $F_{\text{max}}$ and $S$ are conflicting functions with respect to $a$ and $b$. Hence, we formulate this problem as a multi-objective optimization problem, where the conflicting objectives, $F_{\text{max}}$ and $S$, are to be minimized. The problem is mathematically formulated as shown in (6).

\[
\begin{align*}
\min & \quad f = (F_{\text{max}}, S)^T \\
\text{such that} & \quad 0 < a, b \leq 0.5 \\
& \quad 5^\circ \leq \theta_{\text{min}} \leq 10^\circ \\
& \quad D_{\text{min}} \leq D \leq H \\
& \quad i = n - 1
\end{align*} \tag{6}
\]

Here, $D_{\text{min}}$ is the minimum link length required to climb the step of height, $H$, calculated as shown in (7).

\[
D_{\text{min}} = \frac{H}{n(1 - \sin(\min(\theta_{\text{min}})))} \tag{7}
\]

We use NSGA-II [18], a multi-objective optimization algorithm, to evaluate the pareto front. Using the pareto-optimal solutions, one can choose a solution based on other design factors and requirements. Fig. 5 shows the pareto optimal fronts obtained for different wheel pair configurations, and Table II shows the final design parameters chosen.

Further, the thickness of the scissor links needs to be optimised between maximum stress, deformation due to bending and buckling. Also, while optimising the thickness, the space for the placement of the linear actuators between the scissors has to be maximised. Given the problem, a simplified model of the scissor lift mechanism with two crosses used in the prototype was imported to ANSYS 17.1 for structural simulation analysis. This model refers to the maximum extended position of the scissor lift mechanism. Two commonly used materials – Steel and Aluminium, each with four commercially available
TABLE II: Design specifications for the developed prototype.

| Parameter | Datasheet Values | Final values used |
|-----------|------------------|-------------------|
| $F_{max}$ | 576,840 N        | 1000 N            |
| S         | 0.242 m          | 0.25 m            |
| a         | 0.499 m          | 0.5 m             |
| b         | 0.158 m          | 0.16 m            |
| $\theta_{min}$ | 10°  | 10°               |
| D         | 0.409 m          | 0.4 m             |
| n         | 2                | 2                 |
| t         | N/A              | 3 mm Steel        |

and relevant thicknesses – 2 mm, 3 mm, 5 mm and 7 mm – were selected for the simulation study.

The factor of safety due to the maximum stress ($N_S$), and the absolute maximum total deformation ($\delta_{max}$) and its components in X - ($\delta_{max,X}$) and Y-direction ($\delta_{max,Y}$) were analysed in the ANSYS simulation study. Fig. 6 shows the values of parameters analysed during the study. It is to be noted that $\delta_{max,X}$ signifies the deformation due to bending and buckling of the scissor links. It was found that the safety factors ($N_S$) for all the four thicknesses considered were similar for both metals. However, aluminium showed a higher maximum deformation than steel with the same thickness both in X- and Y-direction. Selecting a thicker aluminium link would lead to reduced space for the linear actuator. Even so, choosing steel would mean a heavier mechanism. Hence, optimising all the requirements for the prototype developed by us, steel links of 3 mm thickness were used to provide sufficient strength, lower maximum deformation and more space for accommodating the linear actuator. The above-mentioned procedure can be followed to choose various design parameters of the scissor lift mechanism optimally, depending on the size, weight and use case of the robot.

B. Configurable Structure for Agricultural Tools

The overall mechanical structure of the robot is designed to be easily reconfigured in order to accommodate different agricultural tools. The initial prototype showed the potential of including a pesticide/water spraying mechanism and a seed metering module as detachable add-ons. This modularity allows the seamless addition of separate mechatronic solutions for terrace farming activities which allows development of highly efficient solutions for ploughing, seed metering, and water/pesticide spraying etc.

III. EMBEDDED AND SOFTWARE DESIGN

A. Embedded Architecture

TABLE III: Lidar Placement Locations. $N$ is the number of wheel pairs in the robot, which is 2 for the prototype.

| Location                      | Count     |
|-------------------------------|-----------|
| At far ends of all sides      | 2 per side x 4 sides = 8 |
| Downward Facing               | $N (=2$ scissors) + 2(chassis) = 4 |
| Width Estimation (at 45°)     | 2 (one for each side) |
| Failsafe (at 25°)             | 1 per side x 4 sides = 4 |

and the robot estimates its position by fusing the data from wheel encoders, GPS and Inertial measurement unit (IMU). To ensure that the robot stays on the step and at a plausible distance from the wall beside it, VL53L1X 1D LiDAR sensors are employed along with a RGB camera feed (Logitech C310). The entire system is integrated using a Raspberry Pi control unit. The raw data from each sensor is communicated to the micro controller using serial communication protocols.

Robot Operating System (ROS) forms the underlying framework for the integration of various subsystems at the software level. The IMU is placed at the centre of the rotation of the robot. An RGB camera is placed facing forward, mounted at a suitable height. A total of 18 1D LiDARs sensors are placed around the robot, as described in Table III.

b) Power Subsystem: Lead Acid Battery, being cost-effective, resistant to corrosion and overcharging, is used to power the actuators and sensors. Different voltage levels as required by the actuators and sensors are generated using buck-boost converters and supplied to the sub-systems. The micro-controller and sensors work on low voltage levels (5V) whereas the actuators work on higher voltage levels (12V).

B. Perception and Localization

a) Localization: The estimation of the pose and orientation of the robot is done using ground odometry data from wheel encoders and inertial measurements from IMU. As ground odometry tends to be inaccurate in the presence of wheel slipping, it is often fused with other forms of inputs like lidars and GPS for accurate localisation. We use an Extended Kalman Filter (EKF) method to fuse different localisation estimates. The EKF method effectively weights the different estimates with the uncertainty associated with them and outputs the robot position. Based on these low-level inputs, the overall localisation module as shown in Fig. 7, outputs high-level location information that includes the step number (from the top), crop row number and distance from sides of the terrace.

b) Terrace Width Estimation: We use the width estimation lidars $W_l$ and $W_r$ to estimate the minimum terrace width at the current step. These lidars are pointed downwards at an angle of 45° from the horizontal. For the purpose of describing
Using geometry, the terrace step width can be estimated as there is a sudden change in the readings of lidars shown in Fig. 8. A new width measurement is taken when the robot moves such that the terrace wall is towards its left, as the pair of dummy wheels come in contact with the next step. This is done until the front pair of wheels are lifted up by the scissor mechanism while the rear wheels are still in contact with the present step. In the next stage, the front pair of wheels are lifted up by the scissor mechanism when there is a sudden change in its measurement. In LiDAR under the front end of the robot to detect the step with the horizontal surface of the next step. Here we use a switch to second stage. In the second stage, the robot moves to the central dummy wheels to detect contact of the dummy wheels and ensure precise movement. In the fifth stage, the rear wheels are lifted up and in the last stage, the whole robot moves forward and moves to the next step. In every stage, it is ensured that the centre of mass of the whole robot stays inside the friction polygon made by the contact points of the wheels and the surface to ensure its stability. For climbing down, the same stages would be followed in the reverse direction. The same algorithm can be extended to designs with more number of wheel pairs, and as only one wheel pair moves at a given time, the maneuver is extremely stable.

b) Pitch Control: Due to the difference in the mechanical response of both scissor lift mechanisms, the pitch of the chassis while lifting up may not be zero when both the actuators are given the same input causing instability. A PID controller is used to maintain zero pitch ensuring that the robot remains stable at all times while climbing. We estimate the error in pitch and provide corrective feedback to the linear actuators to keep the pitch zero at all times.

$$A_f - A_b = k_p \theta + k_i \int \theta dt + k_d \frac{d\theta}{dt}$$  \hspace{1cm} (9a)

$$A_f + A_b = c_0 + c_1 \dot{\theta}$$  \hspace{1cm} (9b)

Here, $A_f$ and $A_b$ actuator inputs for the front and back linear actuators. $\theta$ denotes the pitch of the robot. This method allows us to achieve two different objectives,

1) Pitch control is obtained by applying a PID controller to control the difference in the actuation inputs to the two linear actuators.

2) Constant velocity of ascent/descent is obtained by approximating the average actuation input using a proportional controller and a DC offset.

We observe that a standard PID performs well during normal operation but the controller performance depletes on addition of a payload and in presence of external forces. A standard PID in presence of an external weight leads to a change in the asymptotic value of the pitch which can cause instability. In order to address this we use an adaptive PID algorithm based on [19]. The algorithm uses a modified version of the MIT rule for altering PID gains given as,

$$k_p(t + 1) = k_p(t) + \gamma_p \cdot [e(t) - e_m(t)]$$  \hspace{1cm} (10a)

$$k_i(t + 1) = k_i(t) + \gamma_I \cdot e_m(t)$$  \hspace{1cm} (10b)

$$k_d(t + 1) = k_d(t) + \gamma_D \cdot \dot{e}_m(t)$$  \hspace{1cm} (10c)

where $\gamma_p, \gamma_I, \gamma_D$ are tunable parameters and $e(t), \dot{e}$ are standard error and error rate measurements whereas $e_m(t), \dot{e}_m(t)$ are filtered values through a low pass filter. This algorithm helps to handle noises in the system effectively while preventing extremely high values for the PID gains. As shown in Fig. 10, we observe improved performance with adaptive PID in comparison to standard PID controller in maintaining zero pitch with external disturbances.
Pure Pursuit algorithm include uneven terrains. The key modifications made to the original central turn angle, for this purpose which takes into consideration the kinematic constraints of the robot and external disturbances due to uneven terrains. The key modifications made to the original Pure Pursuit algorithm include,

- Use of an adaptive look-ahead distance proportional to the velocity of the robot to ensure smooth control inputs.
- An additive gain term supplementing the nominal input which acts as an active damper against the ground reaction forces causing slip.

The modified steering control input is calculated as,

\[ \delta = \tan^{-1}\left( \frac{2L \sin(\alpha)}{I_d} \right) + k_{d,yaw}(r_{ref} - r) \]  

(11)

where \( I_d = l_0 + \beta|v| \), \( L \) is the length of the robot, \( \alpha \) is the central turn angle, \( v \) is the velocity of the robot, and \( I_d \) the lookahead distance parameter. \( r_{ref} \) is the rate of change of yaw for the reference trajectory and \( r \) is the change of yaw for the robot. The added gain of \( k_{d,yaw} \) requires to be tuned based on the range of operating velocity of the robot.

IV. CONCLUSION

This work describes a solution to automation in terrace farming. The robot incorporates a novel step climbing mechanism design, which facilitates climbing terrace steps of variable and higher sizes than previous solutions. The design optimization method based on multi-objective optimization is presented in order to find optimal design parameters for different use cases. The navigation and control algorithms presented also provide a stable performance in real world but require manual fine tuning which could be inefficient. Hence more advanced approaches for controller tuning could be a future direction to explore. Full dynamics modelling of the system and ability to simulate the physics of the system in high fidelity simulators is another avenue of research worth exploring.

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