Theoretical analysis of velocity, acceleration and torque calculation of a five-bar onion transplanting mechanism

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Abstract. The seedling transplanting mechanism is one of the key components of onion transplanter. Therefore, kinematic analysis of the transplanting mechanism is helpful to calculate the operational efficiency and performance of the device. The purpose of this study is to perform theoretical analysis of a five-bar mechanism to calculate the velocity, acceleration and input driving torque as well as to select the appropriate combination of link bars for smooth transplantation of onion seedlings. 3D model assembly of the mechanism was theoretically modelled and its motion was simulated by using commercial software. The five-bar mechanism is comprised of a driving link, driven link, connecting link, slider and the fixed slot. The movement of the slider was constrained to follow a fixed slot pathway, which was the combination of a straight line and a circular path along the driven link bar. Four number of simulation trials were conducted with different lengths of link bars for the selection of the appropriate link combination and respective peak velocities and accelerations. Driving torque was calculated at 30, 40, and 50 rpm speed of the driving link. The simulated velocities and accelerations of the end effector in ‘X’ and ‘Y’ directions for appropriate link combination were found as 0.36 m/sec, 0.73 m/sec and 4.5 m/sec², 4.7 m/sec² respectively. The required driving torque were observed 3.8 Nm at 30 rpm to complete the one cycle of onion seedling transplantation. The outcomes of this study would provide a significant reference for the validation and development of an efficient transplanting scheme for onion transplanting.

1. Introduction
The onion (Allium cepa L.) crop is one of the most widely grown, ingested and highly demand vegetables around the world. Low pungency yellow onion is preferably grown in Korea because it has better storability as compared to the red cultivars [1]. In general, the early and late harvesting times for onion are 135-155 and 165-175 days respectively. The conventional method used for vegetable transplantation is labor-intensive and inefficient which needs 185-260 man-hr/ha [2]. Research and development of plug seedling transplanter were started in the 1980s [3]. Overall transplanting efficiency depends on the mechanism type used in the transplanter. These limitations in the transplanting efficiency
occurred due to the non-vertical deposition of the seedling into the soil and the creation of wide transplanting hole diameter by some vegetable transplanter [4]. An onion transplanter consisting of a 4-bar cam-type seedling planting mechanism manufactured with almost zero relative motion between hopper and forward speed of the device. Optimum operating conditions evaluated and 100% success planting rate were obtained with plating efficiency of 50 seedlings/min [5].

A study was done on the designing and development of a parallel robotic arm consisting of five revolute joint (5R) and two degree of freedom. The developed mechanism was synchronized with mechanical, electronic, logic and program considerations to integrate the automatic handling of the paper pot seedling for field operation. It was reported that a parallel robot arm was suggested to be more suitable for high-speed operation of picking and placing of the paper pot seedlings under a hostile environment [6]. 4-bar link-cam rotary transplanting mechanism was developed. It was suggested that average forward displacement in the rotary method is small [7]. The self-propelled fully automated transplanting mechanism for onion seedlings permits the high speed planting operation and effective for the elimination of laborious tasks because seedling fed and planted automatically by the machine itself [8].

A feasibility study was conducted using computer graphics and simulation for bedding plants transplanting with an industrial robot Puma 560. A computer added parallel-jaw type gripper model was simulated twice to estimate the cycle time for transplanting the seedlings from 392 plug seedling tray to 32 plug seedling growing tray and correlated within 10% of the measured time using the actual robot. The transplanting rate of 11 plants/min was observed [9]. The advancements in the automatic vegetable transplanting system is significantly accepted by farmers which offer an efficient way of planting seedlings [10]. The automatic vegetable transplanter requires either plugs or pot seedlings. [11] Developed a picking device which is able to extract the seedlings mechanically. The device used a five-bar linkage mechanism. The laboratory results showed that the device could extract 30 seedlings/min. The transplanting capacity of four inclined pins was measured as 2800 seedlings per hour with 99% success rate [12]. The highest holding efficiency and penetrating force were obtained at 66-70% of soil moisture and at penetrating angle approximately from 0 to 0.36 degree. The seedling, carrying and management of the high-quality seeds has automated in the seeding factory but transplanting is still manpower dependent and whole process of automation is very demanding [13].

This study presents the computational simulation for the development of a five-bar onion seedling transplanting mechanism prior to the fabrication of a self-propelled onion transplanter. The main objective for this study were to develop a kinematic model of the mechanism and analyzing its motion simulation using SolidWorks software package. The development of a structurally simple transplanting device suitable for onion crop cultivation as per Korean conditions which can transplant the seedling reliably. To calculate acceptable velocities, acceleration and input driving torque required to drive the mechanism and selection of the appropriate link size combination.

2. Materials and Methods

2.1. Structure and working principle

The transplanting device mechanism was consisting of five-link bars: driving link, driven link, connecting link, slider and the fixed slot showed in Figure 1. The driving link initiates the motion to drive the connecting link and driven link in order to move them forward and backward along the slider, which constrained within a fixed slot and complete a cycle. The slider is restricted to follow the straight and circular pathway of the fixed slot. The slider is an integral part of the mechanism attached with the end effector, which extract the seedlings from the cell tray and deposit them into the planting hopper. The end effector reaches the seedling extracting position as it travels outward across the straight line of trajectory motion path shown in figure 1. At this specific position, it extracts the seedling and starts moving rearward across the straight-line path. While the end effector carries the seedling, the slider moves in a reverse direction along a straight path as well as a circular path of the trajectory. The center of rotation of the circular path is located at the pivoted point of the driven link. The end effector
discharges the seedling at the endpoint of the circular route of trajectory motion. This process continues to complete the work cycle and establishment of an automatic onion transplanting mechanism.

Figure 1. Kinematic model of five bar seedling transplanting mechanism.

2.2. Kinematic simulation model and trace path trajectory
Figure 2 shows the kinematic simulation model of the five bar onion transplanting mechanism. Cartesian coordinate system is used to draw the mathematical model of the mechanism. The simulated velocities, accelerations of the end effector and input required torque were measured using (SolidWorks Simulation, Dassault Systems SolidWorks Corp., MA, USA).

Figure 2. Kinematic representation and motion trace path trajectory: (A₀) seedling pickup positions, (A₁) seedling placement position.

The straight-line in the trajectory reflected the motion of the mechanism where at position A₀ the end effector extract and carry the seedling. The circular path in trajectory describe the motion diversion toward the position A₁ a seedling placement position. By substituting the different length size combinations of the bar links, four number of simulation trials were conducted using SolidWorks motion
analysis feature to select the appropriate link combination as well as to measure the respective velocities and acceleration. The simulation for input required torque measurement to drive the mechanism was executed at three different 20, 30 and 40 rpm speed of the driving link.

The mathematical model of the transplanting mechanism can be represented by making a vector loop equation. By taking the 1st and 2nd time derivatives of vector loop equations result in the velocity and acceleration. Therefore, velocity and acceleration of the proposed transplanting mechanism in X and Y direction can be calculated by using equations (1), (2), (3), and (4) respectively. Where \( \omega \) is the angular velocity of the links and velocity and acceleration of fixed link \( L5 \) is zero.

\[
\begin{align*}
\mathbf{L}_1 \sin \theta_1 \omega_1 - \mathbf{L}_2 \sin \theta_2 \omega_2 - \mathbf{L}_3 \sin \theta_3 \omega_3 - \mathbf{L}_4 \sin \theta_4 \omega_4 &= v_x \quad (1) \\
\mathbf{L}_1 \cos \theta_1 + \mathbf{L}_2 \cos \theta_2 + \mathbf{L}_3 \cos \theta_3 + \mathbf{L}_4 \cos \theta_4 &= v_y \quad (2) \\
-\mathbf{L}_1 \omega_1 \cos \theta_1 - \mathbf{L}_2 \omega_2 \cos \theta_2 - \mathbf{L}_3 \omega_3 \cos \theta_3 - \mathbf{L}_4 \omega_4 \cos \theta_4 &= a_x \quad (3) \\
-\mathbf{L}_1 \omega_1 \sin \theta_1 - \mathbf{L}_2 \omega_2 \sin \theta_2 - \mathbf{L}_3 \omega_3 \sin \theta_3 - \mathbf{L}_4 \omega_4 \sin \theta_4 &= a_y \quad (4)
\end{align*}
\]

The input torque required to drive the transplanting mechanism can be calculated by using equation (5)

\[
P = \frac{T \times W}{9.549}
\]

Where, \( P \) is power in Watt, \( T \) is torque in Nm, and \( W \) is the rotational speed of the driving link in rpm.

3. Result and Discussion

3.1. Velocity and acceleration analysis

Velocities and accelerations of the end effector for different combinations of link bar lengths and required input torque for different rotational speeds of the driving link were analyzed. The 3D model of the five-bar mechanism was subjected for motion simulation using SolidWorks software. Tables 1 and 2 present the simulation results of the velocities and accelerations of four different link size combinations of the five bar transplanting mechanism. The appropriate lengths combination of mechanism for driving link, connecting link, driven link, end-effector and fixed slot were measured as 58 mm, 102 mm, 120 mm, 110 mm, and 140 mm respectively.

| No. of trials | Driving link (mm) | Connecting link (mm) | Driven link (mm) | End effector (mm) | Fixed link (mm) | Velocity - X (m/sec) | Velocity - Y (m/sec) |
|---------------|------------------|---------------------|-----------------|------------------|----------------|----------------------|----------------------|
| Trail 1       | 54               | 106                 | 116             | 114              | 140            | .307                 | .612                 |
| Trail 2       | 56               | 104                 | 118             | 112              | 140            | .334                 | .670                 |
| Trail 3       | 58               | 102                 | 120             | 110              | 140            | .367                 | .733                 |
| Trail 4       | 60               | 100                 | 122             | 108              | 140            | .365                 | .759                 |
Table 2. Simulation results of accelerations at 30 rpm.

| No. of trials | Driving link (mm) | Connecting link (mm) | Driven link (mm) | End effector (mm) | Fixed link (mm) | Acceleration - X (m/sec^2) | Acceleration - Y (m/sec^2) |
|---------------|-------------------|----------------------|------------------|-------------------|------------------|-----------------------------|-----------------------------|
| Trail 1       | 54                | 106                  | 116              | 114               | 140              | 3.3                         | 3.2                         |
| Trail 2       | 56                | 104                  | 118              | 112               | 140              | 4.0                         | 3.6                         |
| Trail 3       | 58                | 102                  | 120              | 110               | 140              | 4.5                         | 4.7                         |
| Trail 4       | 60                | 100                  | 122              | 108               | 140              | 4.8                         | 5.4                         |

Figure 3 and 4 show the graphical representation of the simulated velocities and acceleration of the end-effector against the different link size combinations for the transplanting mechanism. The peak velocity and acceleration of the end effector in ‘X’ and ‘Y’ directions for appropriate link combination were found as 0.36 m/sec, 0.73 m/sec and 4.5 m/sec^2, 4.7 m/sec^2 respectively.

Figure 3. Simulated velocities of the end effector of five bar transplanting mechanism.

Figure 4. Simulated accelerations of the end effector of five bar transplanting mechanism.
3.2. **Torque analysis**
The essential data of mass and inertia were generated within (SolidWorks Simulation, Dassault Systems SolidWorks Corp., MA, USA) and steel material properties were selected for the simulation model. The peak torque for 20, 30 and 40 rpm were observed 1.9 Nm, 3.8 Nm, and 7 Nm as shown in figure. The peak acceleration was observed when the driving link rotational speed increased from 30 to 40 rpm. Therefore, the seedling missing and dropping may occur at peak acceleration. The 30 rpm speed were observed to be feasible to meet design conditions.

![Figure 5](image.png)

**Figure 5.** Simulated input torque of the driving link at 20, 30, and 40 rpm.

Figure 5 shows the simulated input torque required to drive the device for 20, 30, and 40 rpm. The required driving torque was observed 3.8 Nm at 30 rpm to complete the one revolution of onion seedling transplantation in the counter-clockwise direction.

4. **Conclusions**
The maximum velocity and acceleration of the end effector in ‘X’ and ‘Y’ directions for appropriate link combination were found as 0.36 m/sec, 0.73 m/sec and 4.5 m/sec2, 4.7 m/sec2 respectively. The required driving torque was observed 3.8 N-m at 30 rpm to complete the one revolution of onion seedling transplantation in the counter-clockwise direction. The outcomes of this study would provide a significant reference for the development of an efficient transplanting scheme for onion transplanting.

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