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Dimensional synthesis and kinematics simulation of a high-speed plug seedling transplanting robot

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ABSTRACT

To improve the automation and efficiency of plug seedlings transplanting in greenhouse, a high-speed plug seedling transplanting robot was designed by making use of a 2-DOF parallel translation mechanism with a pneumatic manipulator. According to the coordinates of healthy seedlings, the manipulator was driven by the mechanism to fetch and plant seedlings in a planned path. Based on the inverse kinematics of parallel mechanism, a global comprehensive performance index was proposed to synthesize a set of optimized dimension parameters for a good dynamic performance throughout the entire workspace. In accordance with the motion demand of transplanting robot, trajectory planning was carried out and quintic polynomial motion law was taken as the principle of operation for the manipulator. Based on the mechanism dimensions and assembly mode, a virtual prototype model was built, and kinematics simulation carried out. The simulation results were identical to the planed trajectory and a single transplanting cycle took 1.08 s, verifying the rationality of the structure design and trajectory planning. Also, the kinematic parameters were obtained to provide a theoretical basis for optimization design and practical control of the physical prototype.

1. Introduction

In the greenhouse bedding plant industry, the transplanting of seedlings from high-density tray to low-density tray or pot for further growth is an essential operation. Research on the development of a plug seedling transplanter and its components began in the 1980s (Parish, 2005; Tong et al., 2013). Most of these early transplanters mostly utilized an industrial robot with an end-effector to perform transplanting tasks. Hwang and Sistler (1986) incorporated a robotic manipulator with 5 degree of freedom (DOF) into a commercial mechanical transplanter for field transplanting of peppers in pots. Its transplanting rate is slightly more than 6 plants/min. Kutz et al. (1987) used computer graphics and simulation to study the feasibility of bedding plants transplanting using an industrial robot. The simulation results was validated by testing with a Puma 560 robot and a parallel-jaw-type gripper to transplant seedlings from 392-cell plug flat to 36-cell growing flat. The average cycle time to transplant one 36-cell growing flat was 3.3 min (11 plants/min), the transplanting time of a single seedling was 5.5 s. Ting et al. (1990a, 1990b) studied the operation within a prototype workcell having a selective compliance assembly robot arm (SCARA) type robot with a sliding-needles sensor (SNS) gripper. This gripper, equipped with a capacitive sensor, was installed on the wrist of a robot to assure each cell was filled in the growing flats. The transplanting time of a single seedling was 2.60–3.25 s (18–23 plants/min). However, this type of automatic transplanter using industrial robot failed to receive the needed promotion as a results of its complicated structure (having more than 3-DOF) and low efficiency (lower than 25 plants/min). It was also found to be incapable of being assembled with other facilities for greenhouse automated activities (Simonton, 1992; Ryu et al., 2001; Zhang et al., 2009).

New types of transplanters with door frame structure have been developed since 2000s. This kind of transplanters often require two independent mechanism to simultaneously drive manipulator for horizontal and vertical movement. The manipulator used Cartesian coordinate axes to specify the position of the end-effector and seedlings. Linear motion along the two axes was performed using slide actuators. Linear-motion guides were attached to ensure the linear motion along the axes and reduce vibration of the actuators. The linear-motion guides and the actuators were supported and connected by an aluminum frame. For instance, Ryu et al. developed a transplanter for bedding plants in a greenhouse and its transplanting rate was 30 plants/min (Ryu et al., 2001; Choi et al., 2002). In China, Zhou et al. (2009) developed a transplanter

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Nomenclature

O'	the reference point of moving platform
r	the position vector of reference point O'
i	the serial number of kinematic chains which between 1 and 2
θ_{1i}	the position angle of active arm of ith kinematic chain, deg
θ_{2i}	the position angle of followed arm of ith kinematic chain, deg
u_i	the unit vector of active arm of ith kinematic chain
w_i	the unit vector of followed arm of ith kinematic chain
L_2	the length of followed arm, mm
e	the center distance between 2 motor shafts, mm
e_{max}	the maximum allowable value of e, mm
e_{min}	the minimum allowable value of e, mm
θ_m	the upper limit of position angle of active arm, deg
θ_n	the lower limit of position angle of active arm, deg
D	the reachable workspace of the reference point O'
D_t	the workspace of manipulator
b	the width of D_t, mm
h	the width of D_t, mm
H	the distance between D_t and x-axis, mm
β_i	the acute angle between u_i and w_i, deg
β_{min}	the minimum allowable value of β_i, deg
$[\beta]$	the allowable value of β_i, deg
δ	a factor reflecting the relationship between workspace and mechanism dimension
δ_{max}	the maximum allowable value of δ
κ	the condition number of Jacobian matrix J
$\max(\kappa)$	the maximum of κ in workspace D_t
$\min(\kappa)$	the minimum of κ in workspace D_t
σ_1	the minimum singular values of Jacobian matrix J
σ_2	the maximum singular values of Jacobian matrix J
$\bar{\eta}$	a global operating performance index
$\tilde{\eta}$	another global performance index
w_η	the weighted factor of $\tilde{\eta}$
η	the global comprehensive performance index
S	the total displacement of manipulator for each transplanting trajectory, m
T	the period of manipulator for each transplanting trajectory, s
s	the displacement of manipulator, m
v	the velocity of manipulator, m/s
a	the acceleration of manipulator, m/s^2
a_{max}	the maximum allowable value of a, m/s^2
j	the jerk of manipulator, m/s^3
t	the time, s
$\dot{\theta}_{i_{max}}$	the maximum angular velocity of ith active arm, deg/s
$\ddot{\theta}_{i_{max}}$	the maximum angular acceleration of ith active arm, deg/s^2
$\tau_{i_{max}}$	the maximum torque of ith active arm, N m
P_{imax}	the maximum power consumption of ith active arm, kW

applied to multi-spec potted tray and its transplanting rate was 20–25 plants/min. Qiu et al. (2010) subsequently also developed a plug seedlings automatic transplanter for vegetables and flowers. Also, some commercial transplanter systems were developed in western countries (Gao et al., 2012). VISSER Company (Netherland) and Transplant System Company (Australia) developed a series of automatic transplanting machines with 2–32 grippers respectively, the transplanting rate is 1000–1600 cycle/h. The transplanting capacity of a single gripper is lower than 30 plants/min. The above analysis shows that a single transplanting cycle for these transplanters based on door frame structure is more than 2 s.

Diamond is a novel 2-DOF translational parallel robot with advantages of large-stiffness, high-speed, light-weight and low-cost (Huang et al., 2001). Due to its parallelogram structure, the manipulator can obtain a 2-D translation at a high speed in a plane. As of now, it has good application in some fields of light industry for pick-and-place operations, such as quality inspection of rechargeable batteries and soft-bags packing. (Huang et al., 2013).

The specific objectives of this study were (i) to develop an automatic transplanting robot based on 2-DOF translational parallel mechanism to improve the flexibility and efficiency of transplanting. (ii) to synthesize a set of optimized dimension parameters for the transplanting robot to achieve a good dynamic performance throughout the entire workspace. (iii) to plan the transplanting trajectory and set up the kinematics simulation to validate the rationality of the structure design and trajectory planning, as a basis for parameters in prototype's practical control.

2. Materials and methods

Fig. 1 shows the high-speed plug seedling transplanting robot with a 2-DOF translational parallel mechanism used in the study. This mechanism consists of two branch chains made of active arms and followed arms, moving platform and manipulator. Each branch chain contains two parallelogram bar groups. Revolute joint is adopted between members, and 2D translation of the moving platform can be achieved under the driving of two servomotors. Due to the driving motors are fixed on the frame and followed arms are made into light bar, so as to enable the moving platform with high speed and acceleration as well as meet the high-speed and short-medium distance transplanting demand for plug seedlings. The manipulator is fixed on the moving platform to pick up the healthy seedling from the plug of supplying tray and then plant it to the corresponding plug of planting tray. The intermittent feed of the trays is achieved by the conveying system.

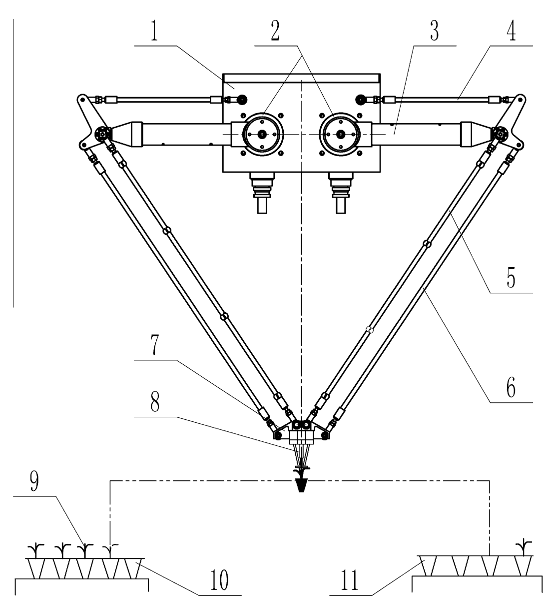

Fig. 1. Sketch of plug seedling transplanting robot. 1. Frame 2. Servomotor 3. Inner active arm 4. Outer active arm 5. Inner followed arm 6. Outer followed arm 7. Moving platform 8. Manipulator 9. Plug seedling 10. Supplying tray 11. Planting tray.