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High dynamics and high accuracy parallel robot for pick and place applications

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Abstract

In this paper, a 5R symmetrical parallel robot for pick and place applications is presented. It reaches an acceleration of 150 m·s^{-2} and a speed of 5 m·s^{-1} with high position repeatability, high position stability as well as low settling time. The robot is driven by two high power torque motors equipped with high resolution rotary encoders. In addition, a novel spatial encoder is mounted on the end effector, which measures five degrees of freedom and extrapolates to the position of the tool centre point. A novel dual feedback control strategy combines the position data of the rotary encoders and the spatial encoder. A prototype has been developed for a workspace of 300 mm × 300 mm. The design of the robot links has been optimized using coupled mechatronic simulations to minimize settling time. The dual feedback control scheme has been optimized for highest bandwidth in combination with high position accuracy of the tool centre point. Test results demonstrate the effectiveness of the mechanical design, the tool centre point measurement and the control strategy.

Parallel kinematics robot, high dynamics, high accuracy, low settling time.

1. Introduction

For die bonding and component placement, the industry requires highly accurate pick and place machines. However, for high throughput the machines should also have high dynamics and low settling time. Serial kinematics machines lack high dynamics as they need to carry the actuators. Parallel kinematics machines overcome this problem by having non-moving actuators [1]. However, it is difficult to achieve low position jitter and low settling time due to the coupled nature of the parallel kinematics. Accuracy of parallel robots, while in operation, can be improved by using redundant sensors [2], especially by directly measuring the end effector pose [3]. Researchers have successfully used the measurement of the end effector pose to control parallel robots [4]. However, using the end effector pose information for control severely restricts the achievable bandwidth for the controller, thus resulting in even larger settling time and higher position jitter.

In the present work, a novel dual feedback technique for parallel robot has been developed. It uses rotary encoders in combination with direct tool centre point (TCP) measurement to achieve accuracy while preserving bandwidth for low position jitter and small settling time. To evaluate the effectiveness of the control strategy, different measurement setups were used. The following sections present the robot architecture, control strategy, performance measurement setups and results.

2. Parallel robot architecture

To achieve high dynamics, a planar 5R symmetrical parallel mechanism has been designed. The dimensions of the links were optimized to have a square workspace of 300 mm × 300 mm. By restricting the workspace, all the singularities associated with a five bar parallel robot are avoided. A prototype of the robot is shown in figure 1. The robot is driven by two torque motors capable of providing 350 Nm of torque with a current of 40 A. To reach these currents at the velocity of 5 m·s^{-1}, a bus voltage of 400 V is used. The motors are equipped with rotary encoders with resolution of 43 nrad. In addition, a spatial encoder measures five spatial degrees of freedom (x, y, Rx, Ry, Rz) of the end effector. These five measurements are then used to extrapolate to the TCP (x, y) position. An air bearing on top of the TCP, sliding with respect to an additional granite mounted above the workspace on a massive beam, enables the robot to carry out processes that require vertical forces up to 500 N.

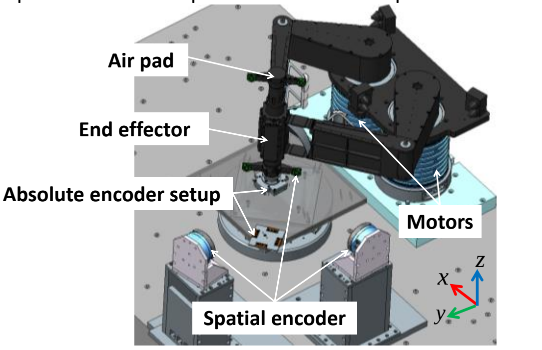

Figure 1. Prototype of 5R parallel robot with absolute encoder setup. The air-pad support beam and top granite has been hidden for clarity

3. Control strategy

The basic control strategy is shown in figure 2. For the position controller, the control action is carried out in the Cartesian space ($\boldsymbol{X}$). The required forces generated by the controller in Cartesian space are projected in the motor space ($\boldsymbol{Q}$) as desired torques using appropriate transformations [4].

The position control algorithm is shown in figure 3. Such architecture simplifies tuning PID and filters as the loop shaping is carried out on an identified transfer function in Cartesian space. For the prototype of the parallel robot, the structure of the arms was optimized using coupled mechatronic simulations for achieving lowest settling time. As a result, the first structural eigenfrequency is at approximately 200 Hz which allows for a controller bandwidth of about 90 Hz.

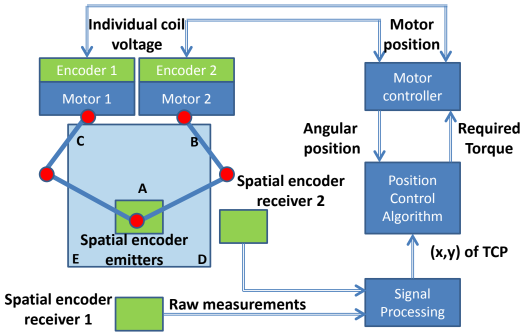

Figure 2. Control strategy for the parallel robot

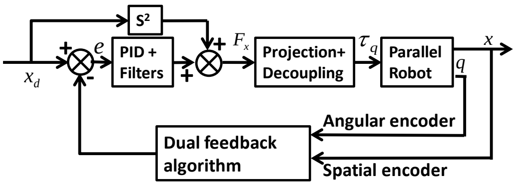

Figure 3. Position control algorithm

4. Performance measurement setups and test results

During movement, the rotation of the end effector which is attached to one arm of the mechanism presents many challenges in using standard position measurement setups for obtaining the external reference position.

For high resolution repeatability measurements, a setup using four absolute encoders with a resolution of 1 nm was developed, see figure 1. This setup of four absolute encoders allows for a very precise repeatability measurement in x, y and Rz, albeit at a very limited number of reference points.

Since the absolute encoder setup is unable to carry out full stroke measurements, a laser interferometer was used in a second setup for external reference position measurement. However, due to the rotation of the end effector, the stroke is restricted to 50 mm and the relatively heavy retro-reflector mounted at the TCP also degrades the performance of the robot.

The repeatability of the robot was measured using the absolute encoder setup at five target positions marked in figure 2 as A-E for strokes of 100 mm approaching from several directions. The TCP's position error at the end of the stroke is measured 20 times and compared.

Since the robot has been developed for high throughput processes, the repeatability is given for a typical user process of 100 ms after the TCP position has settled into a window of 1.5 µm. The typical settling time of the robot is about 30 ms, and hence the final position of the TCP was calculated as the mean position over a time window between 30 ms and 130 ms after the theoretical end of the stroke.

During the experiments, the peak acceleration was reduced from 150 m·s^{-2} to 120 m·s^{-2} due to the high weight of the encoder setup at the bottom of the TCP which limited the jerk to 5000 m·s^{-3}. Table 1 presents the 3σ position repeatability of the robot at the end of the 100 mm strokes and the highest respective position jitter measured for duration of 100ms along the x and y directions. The robot's repeatability of < 2 µm (3σ) with a position jitter < 0.15 µm exceeds the performance of a parallel kinematics topology and reflects the benefit of using the novel dual feedback scheme. In fact, the major advantage of the spatial encoder is to mitigate the thermal effects, which are very difficult to model and compensate otherwise. Furthermore, this is accomplished without compromising the controller bandwidth, and consequently, the settling time.

Table 1. Repeatability for a stroke of 100mm at 120 m·s-2 with 20 experiments in each direction and the jitter observed over 100 ms

Position	3σ/µm in X	3σ/µm in Y	No of directions	Jitter 3σ/µm
A	1.14	1.02	8	0.15
B	0.75	1.47	3	0.12
C	1.98	1.04	3	0.13
D	0.79	1.06	3	0.08
E	1.23	1.28	3	0.08

As shown in figure 4, even during a temperature variation of 3°C in the robot arms attached to the motors, a repeatability of 1.7 µm (3σ) could still be achieved which is a fourfold improvement over the robot's strongly reduced native repeatability under these conditions.

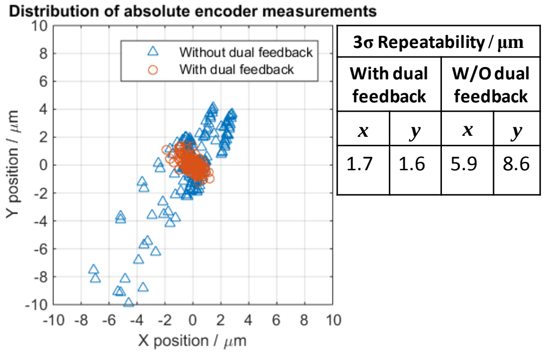

Figure 4. Advantage of dual feedback under temperature variation

A dynamic measurement of the TCP's position with the laser interferometer showed that for a 50 mm stroke, the complete move including the position settling into a window of 1.5 µm is completed within 100 ms. However, due to the heavy retro-reflector, jerk time needed to be adjusted based on the final position of the TCP. Shorter settling times are expected without the heavy retro-reflector.

5. Conclusion

A high accuracy and high dynamic parallel robot is presented in the paper. The robot can achieve an acceleration of 150 m·s^{-2} and a velocity of 5 m·s^{-1}. Using a novel spatial encoder and a dual feedback strategy, a position repeatability of less than 2 µm (3σ) is achieved with a position jitter of less than 0.2 µm (3σ). Under temperature variation, a fourfold improvement over the native repeatability of the parallel robot is achieved. A move and settle time of less than 100 ms is reached at the TCP level for 50 mm strokes. Therefore, the proposed parallel robot is suitable for processes where high accuracy is required at high throughput.

With the current measurement setups, high repeatability of the robot has been demonstrated on a set of reference points. Hence, future developments will focus on the qualification of global positioning accuracy of the robot.

References

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