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A b s t r a c t

Title	Integrated Trajectory Planning and Vibration Suppression of Transfer Robots

(800 words)

Automatic transfer systems are utilized to a great extent in various type of modern industry. Such systems can transfer industrial work pieces in high speed with relatively consistent performance. The cycle time reduction gained by utilization of such systems can increase throughput of the factory. However, high speed operation often results in residual vibration as side effect, usually considered undesirable in many industrial applications that require high precision such as semiconductor wafer pick-and-place system, where a multi-link robot arm is used to automatically pick up, transfer, and place semiconductor wafers. Vibration of the arm tip that occurs after the robot motion causes the robot to wait for a moment until the vibration settles to an acceptable level before performing next operation. This settling time should be reduced as much as possible in order to increase production rate in semiconductor factory.

Other type of vibration problem caused by motion of the robot arm is sloshing, or the vibration of liquid surface. Sloshing is not caused by the vibration of the mechanical structure of the robot. Instead, it is caused by the motion in the task space of the container held by the robot arm. Sloshing may cause the liquid to spill out of the container, and in the case of molten metal too much sloshing may affect the physical properties of the liquid. Moreover, other task, e.g. pouring, cannot be performed when residual sloshing still occurs, thereby potentially reducing the system productivity.

The main challenge in this kind of problem is to generate trajectories with concurrent consideration of motion time minimization and vibration (or sloshing) suppression for point to point motion in a three dimensional working space where static obstacles may exist. Minimizing motion time means that the trajectory should be designed in the joint space, where the main constraints of robot motion exist, for example the kinematic and dynamic constraints of the joint actuators. On the other hand, the existence of obstacle or working boundary of the robot means that the solution has to consider the task space constraints as well. In addition, the vibration suppression should not increase the motion time too much.

This research proposes an integrated framework of trajectory planning and vibration suppression of multi joint robot arm to generate trajectories with quick motion time and low vibration. The framework uses two building blocks: cubic spline trajectory and input shaping. The cubic splines trajectory has a few favorable properties, for example the limited jerk, which provides smoother profile than acceleration-limited trajectories, and the quick computation. Nonetheless, it is relatively fast compared to other higher degree polynomials. A cubic spline trajectory is composed of several curve segments, each is represented by one cubic function. The

segments are bounded by knots. The shape of each cubic curve is determined by four parameters of the cubic function. The trajectory has to be continuous in position, velocity, and acceleration throughout the whole time. By simplification, a system of linear equations involving the knot values, the segment times, and the accelerations can be obtained.

Input shaping method is a simple yet effective method to reduce system vibration. Using value of natural frequency and damping ratio of the vibrating system, the command input signal is decomposed into two. The magnitude and time between those two signals are set such that the second signal can compensate vibration coming from the first signal, thus effectively eliminate subsequent vibration. The input shaping has found practice in many real applications due to the combination of its simplicity and good performance. From the basic principle of input shaping, researchers have come with numerous developments and modifications, resulting in many types of input shapers for different kind of applications.

The framework is formulated as a non linear optimization model with motion time as the main objective function. The constraints consist of the joint constraints (e.g. velocity and torque limit) and task space constraints (e.g. working boundary and obstacle avoidance). The decision variables are both the segment times and the knot values. This gives the framework enough flexibility to achieve quick motion time and to avoid obstacles at the same time.

The integrated framework is applied for two practical cases: a semiconductor wafer transfer robot arm and a liquid container transfer robot arm. In the first case, a three-link planar robot arm works in small bounded working space. In some area, the working space is so small such that the motion of the last link is constrained to a straight line only. In the second case, the system uses a seven degree-of-freedom robot arm that works in three dimensional space, where obstacle may also exists.

Through simulation and experiments, the effectiveness of the proposed solution in generating quick motion while keeping vibration (or sloshing) low is demonstrated. With only small increase in motion time, the vibration can be suppressed to a substantially smaller amount. The calculation time of trajectory generation without vibration consideration is quick. If integrated with vibration suppression, the calculation takes somewhat longer time, but is still acceptable for offline calculation.