Motion Control and Stability Improvement of Autonomous Mobile Robots with Suspended Wheels

Guoliang ZHONG
Candidate for the Degree of Doctor
Supervisor: Yukinori KOBAYASHI
Division of Human Mechanical Systems and Design

Introduction

Mobile manipulators have been given extensive attention in recent years since they have many applications such as materials transport and service for disabled persons. A mobile modular manipulator is normally composed of an m-wheeled mobile platform and an n-degree-of-freedom (DOF) onboard modular manipulator. This combination extends the workspace of the entire robot dramatically. Building up the dynamic model for such kind of robots is a challenging task due to the interactive motions between the manipulator and the mobile platform. Also the vibration control is an important research topic in mobile robots, especially when robots move through rough terrain. As for a mobile manipulator, the trajectory tracking task becomes even more complex and difficult to achieve since the platform and the manipulator move simultaneously. Furthermore, stability is another concerning issue since the probability of tip-over increases due to this kind of mechanical structure.

To ensure steady movement of robots on rough terrain, usually suspension systems are installed between the wheels and the platform to absorb the vibration induced by road. Typically, Figs. 1 and 2 show a suspended wheeled robot called Seekur and a suspended manipulator, respectively. Seekur is a large, all-weather robot that can traverse rugged terrain. The suspended mobile manipulator can achieve tasks in the field so that more and more researchers have been devoted to the researches involving this kind of robot. This study focuses on the suspended wheeled mobile robot and deal with the following problems: Firstly, mobile robots with suspension system can absorb vibration induced by rough roads, but due to center-of-gravity (CG) shift and the dynamic of manipulator, the suspended platform is subject to vibration when the robot moves with acceleration. Secondly, trajectory tracking of a mobile platform and a manipulator simultaneously is a challenging work because of its complex nonlinearity and dynamic interaction between the platform and manipulator. Thirdly, when robots move through rough terrain, it is necessary to improve their stability to eliminate external interference that degrades the performance of vision systems. Finally, although teleoperation has been a benefit to remote control, how to generate an intuitive user interface for teleoperation is still a troublesome problem.

Vibration Control of Mobile Manipulator

The main configuration of the robot is a three-link manipulator mounted on a suspended platform. Two rear driving wheels and one front caster wheel support the platform, as shown in Fig. 3. The multi-input shaping technique is applied to reduce the vibration of a mobile robot when the manipulator is static. Considering the CG shift, the input shapers evaluating both robustness and settling time are optimized by particle swarm optimization (PSO) with chaos. When the manipulator and suspended platform move simultaneously, the direct path method (DPM) is introduced to model the system considering the dynamics of the manipulator and the interaction between the platform and manipulator. Based on cubic splines, the time-jerk synthetic optimal trajectory is described mathematically by taking account of both the minimum execution time and minimax approach of jerks with kinematics constraints such as the upper bounds of velocity and acceleration. The residual vibration can be reduced by forcing the manipulator along the generated optimal trajectory.
Problem One: Suspended Platform Motion with a Static Manipulator

The robot with an upright static manipulator is illustrated in Fig. 4. The CG is shifted because of the pose of the manipulator. The suspension systems are installed between the rear wheels and platform. The O-XY coordinate system is centered on the mobile platform, the line through centers of the two rear wheels is the X axis, the line perpendicular to the X axis and through the center of the front wheel is the Y axis. Using the Lagrange equation of the second type, the dynamics equation of the system can be obtained as

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx
\end{align*}
\]

where \(x\) is the state vector, \(y\) is the output vector, \(u\) is the control force vector. Furthermore, \(A\), \(B\), and \(C\) are the system, control and output matrices, respectively.

The introduced control strategy consists of a feed-forward control unit and a feedback control unit, and the two units are designed separately, as shown in Fig. 5. The feed-forward control unit involves an optimal multi-input shaping technique. It is used to suppress induced vibration of the reference model at the starting and the stop stages of the robot motion. The motion between the two stages is controlled by a feedback control unit. This study focuses on the starting maneuvers from some prescribed input state to the achievement of uniform rectilinear motion, where a dynamic balance has been reached between a specific Coulomb friction and input torques. A feed-forward controller is developed to reduce the vibration of the suspension system by using optimal ZVD shapers which are optimized by employing the PSO with chaos method.

Two shapers act on the left and right input torques for the robot, and the optimization of multi-input shapers is transformed into an optimization problem of eight variables. Considering the energy of the vibration during motion, the robustness with respect to frequency, the settling time of the system, and the saturation limits of the input torques, the cost function is defined as...
\[ J = \frac{1}{2} \sum_{i=1}^{n} \int_{t_i}^{t_{i+1}} \left[ x(t)Kx^T(t) + u(t)Hu^T(t) \right] dt + k_i t_i, \]

where \( \omega_o \) is the operating frequency, \( \omega_j \) is the design frequency, \( c_i \) is a factor that determines the permissible error range of the frequency, and \( k_i \) is the weighting factor for each operating frequency.

To demonstrate the effectiveness of the proposed method, several numerical simulations are performed. When \( \omega_o = \omega_j = \omega_o \), as indicated by the curves in Fig. 6, both the ZVD and optimal shapers yield lower residual vibration levels than the unshaped response in the pitch direction. Further, the optimal shapers with improved settling time result in a better performance than the ZVD shapers. Figure 7 plots numerous trials based on various frequency errors. In Fig. 7, the optimal input shapers offer better performance than the ZVD shapers when \( \omega_o \in [0.75\omega_j, 1.25\omega_j] \) but at \( \omega_j < 0.75\omega_o \) or \( \omega_j > 1.25\omega_o \) the performance of the optimal input shapers is poorer than that of the ZVD shapers. This result suggests that the improvement of the performance at \( 0.75\omega_j \leq \omega_o \leq 1.25\omega_j \) comes at the deteriorating performance when the operating frequency \( \omega_o \) is beyond this range. Such deterioration can be expected since there is no factor in the cost function to reflect the performance of the optimal shapers in that range.

**Problem Two: Suspended Platform Motion with a Dynamic Manipulator**

The DPM concept is used to obtain a dynamic model that accounts for the interaction between the platform and manipulator. According to the DPM concept, a point on the base platform (preferably its center of mass) represents the translational motion of the system. As shown in Fig. 8, the kinematics of the mobile manipulator system can be developed by using a set of body-fixed geometric vectors to formulate the position and velocity with respect to a representative point \( p \). Using the DPM concept with Lagrange equation, the dynamic model can be represented as

\[ M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = Q, \]

where \( M(q) \), \( C(q, \dot{q}) \), \( G(q) \) and \( Q \) denote the mass matrix, nonlinear velocity vector, gravity vector and torque matrix, respectively.

In order to formulate the trajectory, the cubic splines are applied to each joint to interpolate the joint trajectory between every two neighbor knot points. Then considering the high operating efficiency and low manipulator vibration, the cost function is defined to obtain the time-jerk synthetic optimal trajectory as

\[ f = \min \left( \zeta_T \sum_{n=0}^{N} T_n + \zeta_j \sum_{n=0}^{N} \max \left| J_{n,j}(t) \right| \right), \]

where \( T_n \) is the execution time of the \( n \)th joint, \( \zeta_T \) and \( \zeta_j \) are weighting factors.

Finally, the jerks and the jumps of torque of each joint are decreased after optimization. In consequence, when each joint of the manipulator is forced along the optimal trajectories, the vibrations of the pitch and roll angles are reduced as shown in Fig. 9. These results reveal the effectiveness of the presented PSO with chaos method to solve the contradictory problem between high operating efficiency and low residual vibration using limited control energy. Furthermore, the nature frequencies of the pitch and roll vibrations in problems one and two are different. The causes of this difference may be the relatively large mass of the upright manipulator and the frictions considered in problem one.
The proposed control scheme is a bile manipulator. The main configuration of the mobile manipulator is a modular manipulator mounted on a mobile platform. Two rear driving wheels and one front caster wheel support the platform. Independent motors actuate the two rear wheels, and the caster wheel is free to attain any orientation according to the motion of the robot.

To demonstrate the robustness of the controller, the results of the ACL controller with those of the ACL-RT controller are compared. Through changing the load carried by the end-effector and control law, six different cases shown in Table 1 are examined.

Considering both the trajectory tracking of platform and the trajectory tracking of manipulator simultaneously, case 2 can achieve the best performance by comparing with six cases. Figure 12 shows the trajectory tracking of each joint for cases 1 and 2, where the load carried by the end-effector is 2.00 kg. As shown in Fig. 12, when the ACL controller is used for case 1, each joint of the manipulator tracks the desired trajectory with small error. Moreover, when the ACL-RT controller is used for case 2, the error is reduced.

### Tracking Control Considering Interaction Effects and Uncertainties

The goal of this section is to use adaptive controllers for tracking the trajectory of a three-link mobile manipulator in the presence of modeling uncertainties. In particular, an adaptive fuzzy controller is designed by using the backstepping approach to track the trajectory of a mobile manipulator. To accurately track the trajectory, a fuzzy compensator is incorporated to counteract the modeling uncertainties such as friction and external disturbances. In addition, a robust term (RT) is introduced to reduce approximation errors and ensure system stability.

The main configuration of the mobile manipulator is a modular manipulator mounted on a mobile platform. Figure 10 shows a prototype of the mobile manipulator. Independent motors actuate the two rear wheels, and the caster wheel is free to attain any orientation according to the motion of the robot.

Similar to the above, consider the dynamic model rewritten as

\[ M(q) \ddot{q} + C(q, \dot{q}) \dot{q} + G(q) + F(q, \dot{q}) = \tau. \]

where \( F(q, \dot{q}) \) denotes the modeling uncertainties including friction and external disturbances.

The structure of the proposed control scheme is shown in Fig. 11. Two types of control law are considered as follows:

- The adaptive control law (ACL) is defined as
  \[ \tau = M(q) \dot{q} + C(q, \dot{q}) \dot{q} + G(q) + \hat{F}(q, \dot{q}) - K_p s, \]

- The ACL with RT (ACL-RT) is defined as
  \[ \tau = M(q) \dot{q} + C(q, \dot{q}) \dot{q} + G(q) + \hat{F}(q, \dot{q}) - K_p s - W \text{sgn}(s). \]

To demonstrate the robustness of the controller, the results of the ACL controller with those of the ACL-RT controller are compared. Through changing the load carried by the end-effector and control law, six different cases shown in Table 1 are examined.

<table>
<thead>
<tr>
<th>Case</th>
<th>Load</th>
<th>Control law</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.00 kg</td>
<td>ACL</td>
</tr>
<tr>
<td>2</td>
<td>2.00 kg</td>
<td>ACL-RT</td>
</tr>
<tr>
<td>3</td>
<td>0.30 kg</td>
<td>ACL</td>
</tr>
<tr>
<td>4</td>
<td>0.30 kg</td>
<td>ACL-RT</td>
</tr>
<tr>
<td>5</td>
<td>5.00 kg</td>
<td>ACL</td>
</tr>
<tr>
<td>6</td>
<td>5.00 kg</td>
<td>ACL-RT</td>
</tr>
</tbody>
</table>
Figure 13 shows the trajectory tracking of the mobile platform for cases 1 and 2. For case 2, it can be observed that the proposed ACL-RT controller is able to force the robot to converge to the desired trajectory under the influence of friction and external disturbances. Moreover, for case 1, it can be observed that the desired trajectory is tracked with small error when the ACL controller is employed. As indicated by the results for case 2 shown in Figs. 12 and 13, the proposed ACL-RT controller, which is designed at the dynamic level, accurately tracks the desired trajectory of both the manipulator and platform. This result is obtained because of the application of the fuzzy compensator and RT effectively counteracts the friction and disturbances.

The results demonstrated the effectiveness of the trajectory tracking and the robustness with respect to the dynamic interaction and uncertainties. The proposed method may well make sense to put it into the high precision control of mobile manipulators.

**Dynamic Stability Control of Robots in Rough Terrain**

Semi-active suspensions are mounted between the wheels and platform of a robotic vehicle to absorb the vibrations caused by rough terrain. The semi-active suspension consists of a spring and a magneto rheological damper. Based on the stability criterion, the chaotic PSO (CPSO) method is used to search the optimum semi-active damping characteristics. According to Figs. 14 and 15, the damping coefficient and cost function based on stability measure criterion can be rewritten as follows:

\[
\hat{c} = \max \left( \hat{c}_{\text{min}}, \min \left[ \sigma \left( z_x - \hat{z} \right)^2, \hat{c}_{\text{max}} \right] \right), \quad \left( \dot{z}_x - \dot{\hat{z}} \right) \leq 0, \quad \left( \ddot{z}_x - \ddot{\hat{z}} \right) > 0.
\]

\[
F = \left| \eta - \eta^* \right|
\]

To investigate the dynamic stability measure and the optimal control method, the pavement condition is simulated using the Gaussian disturbance. At this stage, the CPSO is employed to optimize the gain factor. Figure 16 shows the vibratory responses of the robot in the bounce, pitch, and roll motions where it passes through rough terrain when the end effector does not carry a load. The three response curves of the passive suspension are superimposed to evaluate the performance of the proposed optimal control method. As shown in Fig. 16, the vibrations in the bounce, pitch, and roll motions for the optimal controlled semi-active suspension are less than those for the passive suspension. The results indicate that the proposed control method improves the dynamic stability in the three directions when a robot passes through rough terrain.

![Fig. 12 Trajectory tracking of manipulator cases 1 (- - -) and 2 (- - -), and desired trajectory (---).](image1)

![Fig. 13 Trajectory tracking of mobile platform cases 1 (- - -) and 2 (- - -), and desired trajectory (---).](image2)

![Fig. 14 Semi-active suspension system.](image3)

![Fig. 15 Schematic diagram of stability measure.](image4)
Teleoperation of Robots Based on Virtual Reality and WiFi

The teleoperation system consists of virtual environment and wireless communication. In the lower computer, the VC++ is used to develop a control panel for controlling the robotic platform, and WINCAPS III to establish a virtual reality interface for controlling the manipulator. Then the remote desktop of the lower computer is accessed from the upper computer via WiFi. On the upper computer, operator can manipulate the robot by using the received remote control console.

Then the teleoperation system is performed on the experimental robot to grasp a ping-pong ball indoors. In this experimental robot, the lower computer is an Endeavor NP30S Mini-PC with usb WiFi adapter, the robot arm is a VE026A articulated manipulator with 6-DOF. The upper computer is a commonly-used computer.

Figure 16 shows the poses of the manipulator during grasping movement. At this time, the manipulator is teleoperated by virtual manipulator which is transmitted from the lower computer to upper computer via WiFi. Figure 17 shows the poses of the virtual manipulator in virtual environment during grasping movement. It can be found from Figs. 16 and 17, the poses of the real manipulator is consistent with the virtual manipulator, which implies that it is feasible to control the manipulator remotely by using the teleoperation system.

Conclusions

The thesis focused on a suspended wheeled robot and studies the vibration reduction, tracking control, stability improvement, and teleoperation of the robot.

In regard to vibration suppression, methods were investigated to reduce vibration for a mobile robot with a suspension system considering the CG shift. Results show that the optimal input shaping outperforms the ZVD shaping both in vibration reduction and in robustness. In addition, the problem of minimum time-jerk trajectory generation was studied to reduce the vibration when the manipulator and the platform move simultaneously. The vibrations of the suspended platform can be suppressed when the manipulator moves following the optimal trajectory.

In regard to tracking control, a dynamic model considering the interaction between platform and manipulator were constructed. The results demonstrated the effectiveness of the proposed control scheme in the trajectory tracking of platform and manipulator simultaneously.

In regard to stability improvement and teleoperation, the contribution of this study is twofold: concept and design. Conceptually, this study proposed a novel idea to measure the dynamic stability. Design-wise, a virtual control system was developed for teleoperation. Experiments show that the mobile robot can be remotely manipulated by operator using proposed virtual control.