

Development of a motion simulator for testing a mobile surveillance robot[†]

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Abstract

A 6-axis motion simulator has been developed, in order to regenerate UGV (unmanned ground vehicle) motion and to test the stabilization system of the mobile surveillance robot that is mounted on the UGV. For developing the 6-axis motion simulator, a simulation-based design procedure was introduced. The 3D geometric model of the motion simulator was created by using 3D CAD modeler ProE. The multibody dynamics model of the motion simulator has also been created by using the general purpose dynamic analysis program ADAMS to validate the design of the motion simulator. Dynamics and control co-simulation model for the motion simulator has been also established for control performance analyses. Actual hardware of the motion simulator has been fabricated based on the proposed simulation based design. Hardware test of the motion simulator has been tried to validate the design.

Keywords: 6-axis motion simulator; Unmanned ground vehicle; Co-simulation; Multibody dynamics model

1. Introduction

To protect public areas such as airports and seaports from terrorists, an unmanned surveillance robot can play an important role in replacing a human guard. There are several merits in using such a robot system, since the dangerous tasks and hardships of a human guard can be avoided. Currently, the surveillance robot systems are installed at a fixed post to protect specified regions. However, to cover blind spots of a specified area, it is necessary to have a mobile surveillance robot mounted on a UGV system. Therefore, the pan and tilt motion of the surveillance robot must be automatically controlled in order to stabilize the system by compensating the base motion.

Field tests of such a mobile surveillance robot have to spend huge amount of time and sometimes are dangerous. As a result, it is very expensive procedure to test a robot. To reduce the numbers of field tests, a motion simulator that can regenerate UGV motion is a very effective tool to test the mobile surveillance robot in the laboratory environment. The motion simulator is being applied to diverse fields such as the vehicle, aircraft and entertainment industries. Among various types of the motion simulators, the Stewart platform, which is a parallel robot with 6 degrees of freedom, is widely used because it offers higher force-to-weight ratio, high stiffness, as well as better control accuracy over the conventional serial manipulator.[1]

In this paper, in order to develop a Stewart platform type motion simulator, a simulation based design is proposed as shown in Fig. 1. Design verification of the developed motion simulator has been discussed.

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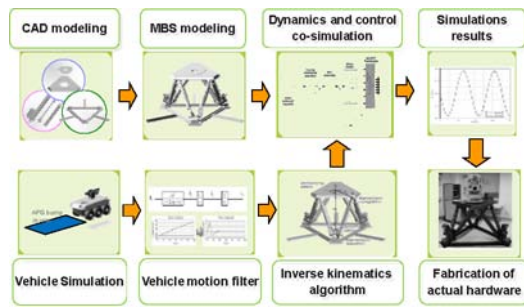


Fig. 1. Simulation based design procedure of a motion simulator.

In Section 2, a 3D CAD model of the motion simulator is introduced and a multibody dynamics model is also described. Section 3 explains the virtual UGV bump run simulations for the test of the stabilization system of the mobile surveillance robot. Data processing with a modified washout filter will be explained in Section 4. In Section 5, inverse kinematic analysis of the virtual motion simulator will be discussed to verify the motion range of the actuators. Dynamics and control co-simulations are explained in Section 6 for control performance of the motion simulator. Actual hardware fabrication and hardware system test will be described in Section 7. Finally, conclusions will be made in Section 8.

2. Motion simulator modeling

In this paper, a motion simulator is designed based on 6-axis Stewart platform. The proposed design specifications of the motion simulator are represented in Table 1.

The motion simulator that is to be developed consists of a moving platform, motors, outer cylinders, inner cylinders, and a base. The 3D CAD model for the motion simulator has been created by Pro-Engineer.

The 3D CAD model has been converted into a multibody model in order to carry out various analyses for design purposes, such as inverse kinematics analysis for the actuator motions with the given moving platform motion, and dynamics and control analysis for verifying control performance. For the multibody model, revolute joints are used between actuator parts and pins, and between pins and the moving platform and the base. Revolute joints are also utilized between the outer cylinder and the ball-screw. A cylindrical joint is used between the ball-screw and the inner cylinder. The ADAMS model is shown in Fig. 2.

Table 1. The proposed specification of the motion simulator.

List	Unit	Required specification
Heave	m	± 0.23
Roll	deg	± 20
Pitch	deg	± 15
Heave velocity	m/s	± 0.3
Roll rate	deg/s	± 20
Pitch rate	deg/s	± 20
Heave accel.	m/s^2	0.5g
Roll accel.	deg/s^2	200
Pitch accel.	deg/s^2	200

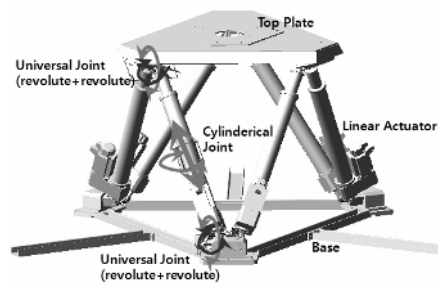


Fig. 2. ADAMS model of motion simulator.

3. Moving platform motion generation using virtual ugv simulation

To evaluate the stabilization control capability of the mobile surveillance robot, actual rough-terrain field tests of the mobile surveillance robot with UGV are necessary. However, it is very difficult to carry out actual field tests, due to cost and preparation of the test fields. Thus, in this research, we performed virtual proving ground test simulation of the UGV model based on the US-Army Aberdeen proving ground for gun stabilization system.[2]

The ADAMS model of the mobile surveillance robot with UGV is as shown in Fig. 3. The virtual test courses for the military tank bump course in the US Army Aberdeen proving ground are as shown in Fig. 4 and Fig. 5.[2] As shown in Fig. 5, A and B type bumps are located in symmetric and asymmetric fashions. The heave, roll, and pitch motions of the UGV can be generated. The Pacejka tire model is utilized for UGV bump run simulation. The bump run simulations with 4km/h constant velocity are carried out. The simulation results are shown in Fig. 6.



Fig. 3. Virtual test model of mobile surveillance robot.

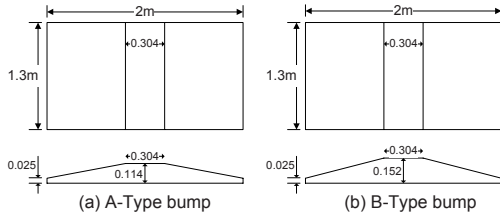


Fig. 4. Type of bump shape.



Fig. 5. Bump course model for virtual test.

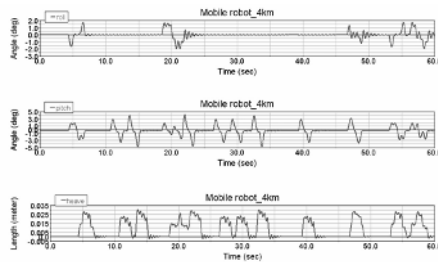


Fig. 6. UGV heave, roll, pitch motion of the virtual test.

4. UGV motion data processing for motion simulator

The moving platform motion data from the UGV simulation, which is described in section 3, contains a translational motion in x, y, z direction and roll, pitch, yaw rotational motion. However, the motion simulator can move with a limited range in x, y directions due to kinematic connections of linkages. Thus, motion data from the UGV simulation must be modified in order to be within the motion range of the motion simulator. We modified a washout algorithm [10], which is used in the driving simulator to satisfy this requirement. Only longitudinal and lateral direction motion data of the UGV are processed by using the modified washout filter. The washout filter block

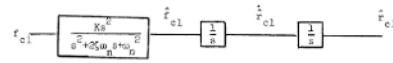


Fig. 7. Washout filter for a translational channel.

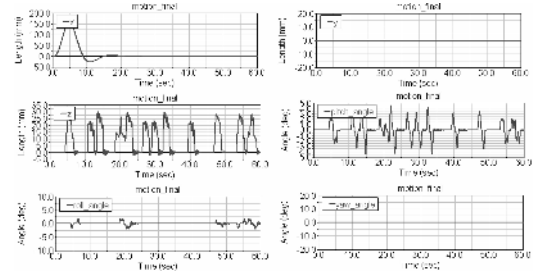


Fig. 8. Filtered motion of the UGV.

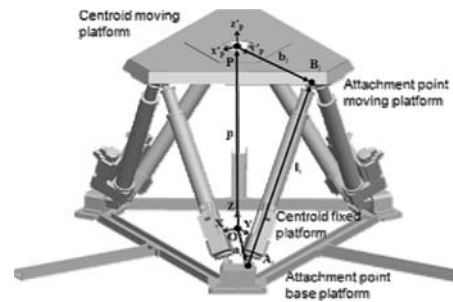


Fig. 9. Vector relationships for actuator length.

diagram used in this research is shown in Fig. 7.

Fig. 8 represents the filtered motion of the UGV. As one can see, longitudinal motion went out to be zero in order to be within the motion range of the motion simulator. This confirms that the modified washout filter works appropriately.

5. Inverse kinematics analysis

To provide control commands to the actuators of the motion simulator, desired motions of the actuators, such as the lengths of the actuators, must be computed from the motion data of the motion platform. Thus, inverse kinematics analysis is necessary to compute the desired motion of each actuator of the motion simulator from the filtered UGV motion data.

According to vector relationships as shown in Fig. 9, actuator lengths of the motion simulator can be calculated. a_i and b_i are known position vectors to points A and B, respectively, as shown in Fig. 9. The position vector p with respect to the inertial reference frame X-Y-Z represents the moving platform position from the filtered UGV motion.

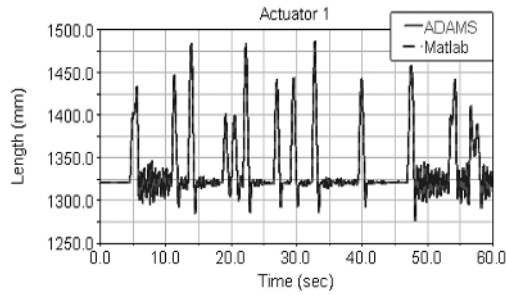


Fig. 10. Comparison of ADAMS and Matlab inverse kinematics.

T is the coordinate transformation matrix from the moving platform reference frame $x'_p-y'_p-z'_p$ to the inertial reference frame $X-Y-Z$. According to the vector definitions, the length of the actuators can be calculated by following equations:

$$|l_i| = \sqrt{l_i^T l_i} \tag{1}$$

where

$$l_i = p + T b'_i - a_i \tag{2}$$

and

$$T = Rot_x(\phi)Rot_y(\varphi)Rot_z(\theta) \tag{3}$$

$$= \begin{bmatrix} \cos \phi & -\sin \phi & 0 \\ \sin \phi & \cos \phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \varphi & 0 & \sin \varphi \\ 0 & 1 & 0 \\ -\sin \varphi & 0 & \cos \varphi \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix}$$

An inverse kinematics program of the motion simulator has been developed by using Matlab.[8] If the filtered UGV motion data is inputted to the program, then the program computes the actuator lengths. To validate the developed inverse kinematics program, results are compared with those from ADAMS simulation. Essentially, identical results are obtained from the Matlab program and ADAMS as shown in Fig. 10. Simulation results also show that the design specification in Table 1 is satisfied.

6. Dynamics and control co-simulation for the motion simulator

The motion simulator must be controlled to follow the desired actuator motion computed from the inverse kinematic analysis described in the previous section. In the design of the actuator of the motion simulator, a motor pulley is connected through the timing belt to the pulley located at the end of the ball-screw element in the linear actuator. To establish the motor model in the multibody model, a rotor body with a revolute joint is introduced and a kinematic

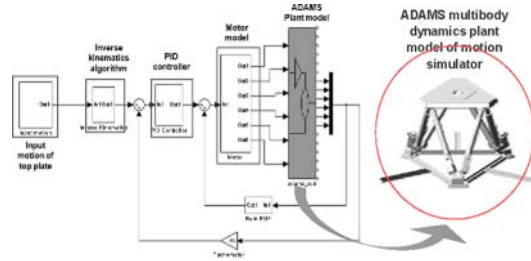


Fig. 11. Co-simulation model for the motion simulator.

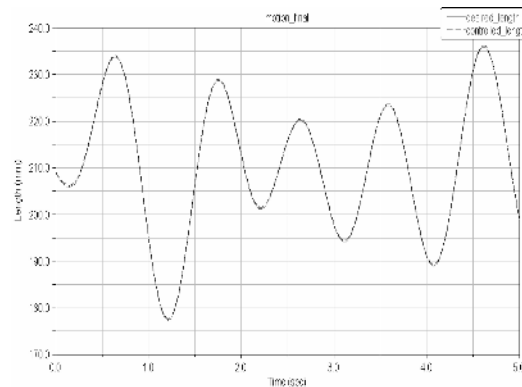


Fig. 12. Control performance of the virtual motion simulator.

coupling constraint is utilized to simulate the timing belt connection. A simple transfer function that converts voltage signals to the motor torque is used to impose the torque on the rotor body shaft. For encoder sensor, a marker (triad reference frame) is used.

Fig. 11 shows the dynamics and control co-simulation model based on ADAMS and Matlab/Simulink. A motion simulator plant model has been established by using ADAMS. The inverse kinematics module, the controller module, and the motor module have been implemented in Matlab/Simulink. For the control modules, a simple PID control algorithm is used.

Dynamics and control co-simulations are carried out with sinusoidal inputs of the motion platform in roll, pitch, and yaw motions together. The roll amplitude of the sinusoidal input is 2° and the frequency of the roll motion is 0.5Hz. The pitch angle amplitude sinusoidal input is 2° and the frequency of the pitch motion is 1Hz. The yaw angle amplitude sinusoidal input is 2° and frequency of the yaw motion is 0.75Hz. Fig.12 shows the comparison between the desired motion and the controlled motion. They are agreed well within the 0.01mm amplitude errors in the actuator length.

7. Actual hardware fabrication of the motion simulator

Based on the 3D CAD model and analysis results described in Section 6, an actual hardware motion simulator has been developed. The joints between the upper plate and the linear actuators are shown in Fig. 13. The axes of two serially connected revolute joints make a right angle in order to have the same kinematic effect as a universal joint. Fig.14 shows the ball-screw element used in the linear actuator. The AC servo motor and the ball-screw element are connected through the timing belt. The pitch of the ball-screw is 10 mm.

The developed motion simulator with the mobile surveillance robot is shown in Fig. 15. The overall system of the motion simulator consists of a 6 axis-

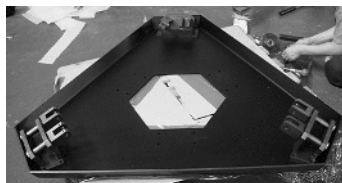


Fig. 13. Top plate of the motion simulator with two serially connected revolute joints.

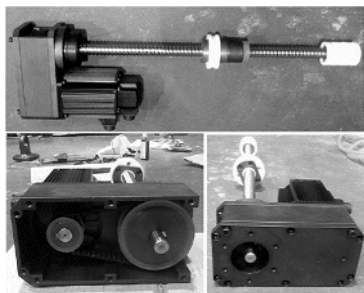


Fig. 14. Ball-screw element of the linear actuator.

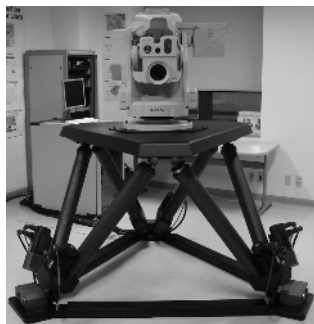


Fig. 15. The developed motion simulator.

Stewart platform type parallel robot, a control cabinet that contains a control PC driven with operating software, motion I/O boards, 6 servo-motor drives. The specification of the overall system of the motion simulator is represented in Table 2.

To verify the control performance of the motion simulator, the sinusoidal inputs described in Section 6 have been also imposed. Fig.16 shows the comparison between the command input motion and the actual responses of the motion simulator in the actuator length. The trend of the actual response is similar to that of the solution shown in Fig.12. However, the amplitude error is bounded within 0.7 mm, and 0.06 sec time delay exists. We speculate the reason that there exists a time delay and amplitude differences is due to the non-linear friction effects of the joints. To compensate the time delay effects, more sophisticated control schemes have to be used.

Table 2. The component specification of the motion simulator.

List	Part	EA	Specification
Parallel Robot	Actuator	6	Servo Motor (RSMH-15BR1ABK3)
	Upper plate	1	Steel
	Upper joint bracket	3	Steel
	Lower joint bracket	3	Steel
Control Cabinet	PC	1	P-4, 1G
	Motion IO card	2	MMC-MI10
	Servo Drive	6	CSD3-15BX2
	Cables	6	
S/W	OS	1	Windows XP
	Programming Language	1	Visual C++

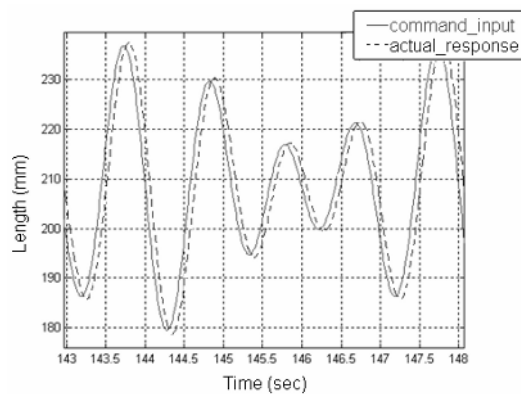


Fig. 16. Prototype motion simulator results comparison between command input motion and actual response motion.

8. Conclusions

A motion simulator that can generate UGV motion for the test of the mobile surveillance robot has been developed based on a simulation based design procedure. A 3D geometric model and multibody dynamics model have been also created by using ProE and ADAMS to carry out kinematics and dynamics analyses. Virtual bump run simulations of the UGV have been performed to generate the motion data of the moving platform of the motion simulator. The modified washout filter algorithm is utilized for the UGV motion data processing. A co-simulation model which contains the inverse kinematics module, the controller module, the motor module, and a 6 axis-parallel robot plant module has been developed. Actual hardware of the system has been also developed and a performance test has been conducted to validate the design. The actual responses of the motion simulator have a similar trend of those from the simulation. This proves that the proposed simulation-based design is effective.

As for the future work, a more sophisticated control algorithm can be applied to reduce the time delay effects.

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