Command Data Compensation for Real-time Tele-driving System on Lunar Rover: Micro-5

Yasuharu KUNII*, Masaya SUHARA**, Yoji KURODA**, Takashi KUBOTA***

* Dept. of Electrical, Electronic and Communication Engineering, Chuo University
  1-13-27 Kasuga, Bunkyo-ku, Tokyo 112-8551, JAPAN.
  E-Mail: kunii@hmsl.elect.chuo-u.ac.jp

** Dept. of Mechanical Engineering, Meiji University
  E-Mail: ykuroda@capecod.mind.meiji.ac.jp

*** The Institute of Space and Astronautical Science,
  E-mail: kubota@nnl.isas.ac.jp

Abstract
In this paper, we discuss tele-driving system for a long driving of a lunar rover and also describe our newly developed small, lightweight lunar rover called Micro-5 and its visual sensor system. An operator uses virtual world simulator to make command path. The virtual environment of this simulator is constructed with measurement data from a rover on the moon.

We have, however, a communication delay between the earth and the moon. So, there is the difference between old map data which operator used for path planning and new data which a rover is tracking on. The operator's path command has less reliability to avoid obstacles and to reach the goal. Therefore, to make high reliability of operator's command, we propose Command-Data Compensation (CDC), which compensates this difference as the distortion of the environmental map.

1. Introduction
Toward the next century, several schemes sending an unmanned mobile explorer to the moon or Mars are being planned for scientific exploration[1][2][3]. In recent years, many researchers have studied and developed lunar or planetary rovers for unmanned surface exploration of planets. Especially micro-rover missions, for example, Sojourner rover(1997), have received a lot of attention, because small, low-cost missions are typically constrained by mass, budget and schedule.

On the other hand, as a part of a development program, tele-operation or autonomous navigation technologies are earnestly studied for realizing a rover to be able to move on an unknown lunar or planetary surface[4]. Nowadays there are few navigation system that can travel safely over a long distance for many days in unknown terrain. However, the wide area investigation, which needs a long distance navigation, is strongly desired by many scientists. Conventional navigation methods are "Wait & Move" method including much waiting time. Rovers have to wait an operator command during an operator's path planning and he/she carefully decides its path for a long time. Additionally, it is difficult to go over a long distance because of
measurement error proportional to the distance and a rover spends much more waste-time in this case. Therefore, if continuous driving, which has less waiting time, are realized, it can be possible to construct a long drive tele-driving system. To compose a long drive tele-driving system, rover should have a low-level intelligence which can understand human intention included in operator's path command for obstacle avoidance.

In this paper, we discuss tele-driving system for a long driving of a lunar rover and also describe our newly developed small, light-weight lunar rover called Micro-5 and its visual sensor system. An operator uses virtual world simulator to make command path. The virtual environment of this simulator is constructed with measurement data from a rover on the moon.

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2. Planetary Rover: Micro 5

2.1. Micro 5

Developed Micro Planetary Rover: “Micro5” is shown in Fig.1. Micro5 is driven by five wheels controlled independently. The steering is controlled by differential of left and right wheels. Small DC motors actuate those wheels. The velocity of the rover is about 1.5[cm/s]. It has the proposed new suspension system called **PEGASUS** (PEntad Grade Assist SUSpension)[5]. So the climb-able step is 0.15[m] and the climbable slope is about 40[deg]. Power is supplied by solar panel on the top of the rover. It’s also driven by on-board batteries.

Two CMOS cameras are used as stereo camera for a forward terrain sensor. It also has other cameras around of the body for navigation and scientific observation. The rover is equipped with pitch and roll clinometers for attitude detection and encoders for dead reckoning. Sensor data processing and control are performed by on board computers, for example, RISC-CPU.

2.2. 5DOF Manipulator & Camera System

Micro Manipulator is mounted on Micro-5 (Fig. 2). It has 5 Degree-Of-Freedom (DOF) serial link structure as shown on Fig. 3. It can perform grasping samples, operating some science equipment and scratching sample surface. Moreover, endeffectors based on the mission will be able to be installed on the top. In this time, the sample collection mission such as small stones is assumed, and a gripper will be equipped. Each joint is driven by Ultra-Sonic Motor (USM) with Harmonic Drive gear, and all of links are produced in a single structure of a carbon fiber. Here, it is forecast that the manipulator is spent much time for a command waiting state etc. In general, USM adopted on this manipulator can drive by a low electric power and has a big geostationary torque. Therefore, the conservation of electric power can be achieved on this manipulator sys-
tem. In addition, we have much advantage because CFRP used for the main body has lightweight and high strength.

On the other hand, this manipulator system is providing another important function to the rover. That is an active visual sensor system. So, three small size C-MOS cameras will be mounted on the elbow and the top of this manipulator, but, in this stage, it has only one camera as a hand eye camera (Fig.3). Whole of visual sensor system on Micro-5 is shown in Fig.4. Four stereo camera systems are located on the each side of the body, and one of those is on the elbow of the manipulator, which is called “Arm Eye Camera”, for a front view (Fig.4 (a)). A hand eye camera and stereo arm eye cameras can be located at the high position by expanding the manipulator and these are working like an observatory. This camera system is useful for the autonomous navigation, the tele-driving and the tele-science. Especially, an environment and elevation map data is acquired by this system, during navigation and tele-driving of the rover.

3. Tele-driving System

3.1. Tele-driving System for Micro-5

In the case of an environment with time-delay caused by a communication delay, it’s difficult to compose a closed loop control structure between a master and slave system. In such a situation, it is necessary to consider about some method to achieve a stable control. Supervisory control system is one of the solutions. However, high-level supervisory control system demands high autonomy, that is, the high performance of a calculation power and sensors. Actually, in the space, it is difficult, in many cases, to install an high-performance computer and various sensors due to problems of the harsh environment, weight of equipments and so on. Therefore, high-level autonomy will not be expected on the system, but we can accept the system based on human direct and continuous tele-control with some low-level intelligence on the rover.

The schematic of Tele-Driving System for Micro-5 is shown in Fig.5. A virtual world simulator is used for an operator's path planning of the rover. The virtual environment, which has virtual Micro-5, is created from received data that have been sent from the real rover on the moon. To create control-command, an operator is controlling the virtual rover in the virtual environment and those data are continuous trajectory data or discrete waypoint data. The created path data is sent to the moon, on where the real rover has been tracking those data. On the other hand, Micro-5 keeps sending the earth the environment data periodically measured by the above-mentioned visual-sensor system, and the virtual environment at the ground station is improved, as shown in Fig.5.

3.2. Distortion of Environment Map data

In Fig.6, the latest path command data of the real rover were created from data based on measurement data of an environment in the past, because of a communication time-delay. However, the real rover is updating measurement data that are more reliable at the moment. We might have a difference between the virtual world on the ground and the latest environment model on the real rover, and command path might cross over an obstacle and that is like the red path in Fig.7. Therefore we have to change
or compensate trajectory data by using the latest measurement data (Fig.7 (b)).

The difference between these measurement data seems to be mainly caused by visual sensing error according to the distance from obstacles, and in this case, the reliability of data that the rover measured from the closer area is higher. The real rover approaches to the remote measured area, consequently an environment map data is more improved. As shown in Fig.7, the received path data: the red path, which was based on old map data and might cross over obstacle, is improved like the blue path.

In this research, we assume that this difference is the distortion of the environmental map between the past and the present data, and we compensate this map distortion, by using a distortion compensation matrix which is the mapping between the old and new environment data.

3.3. Command Data Compensation

Actually, an environmental map has 3 dimensional data, and the map data distortion is also 3D and non-linear. However, in the initial stage of this re-search, let us assume that the map distortion is two dimensions and linear. And, the distortion compensation algorithm of the camera lens is applied to the distortion compensation.

The Command Distortion Compensation (CDC) transformation is as follow.

\[ X \overset{?}{\rightarrow} XA \]

Where \( X \) is sampling data of the old environmental data, \( \overline{X} \) is the latest environmental data, and \( A \) is the distortion compensation matrix. Actually, we need only three pairs of the sampling point (\( X \) and \( \overline{X} \)), if these measurement data have much accuracy. However, measurement data are including a nonlinear noise. So it is better to measure a lot of point, and then we use a least mean square techniques to obtain a suitable linear solution.

In the first, we have to make the orthogonal triangular decomposition by using the householder reflections:

\[ \overline{X}P \overset{?}{\rightarrow} QR \]

where \( R \) is upper triangular matrix, \( P \) is permutation matrix and \( Q \) is orthogonal matrix. Then the least squares approximate solution is given by \( A = P \left( R^{-1} \left( Q^T X \right) \right) \).

Therefore, the command distortion compensation is obtained from

\[ W_{p_{\text{new}}} = AW_{p_{\text{old}}} \]

Where \( W_{p_{\text{old}}} \) is way-point data matrix sampled data created by operator and \( W_{p_{\text{new}}} \) is compensated way-point data matrix.

4. Simulation Results
4.1. Command Data Compensation

Fig.8 is a simulation result of Command Data Compensation in the case of static state. Here, red boxes are obstacles measured in the past as old environment data, and green boxes are new environment data, and, the trajectory (a red line) in Fig.8 (a,b) are operator command data, and a blue line in (b) is compensated data. Belts in Fig.8(c) are the trajectories of a rover (pink belt: operator command, blue belt: compensated data), whose width indicate the size of the rover. The distortion compensation matrix is given at the right hand of Fig.8(c). Old and new map data have 10% error, proportional to the distance from a rover. In Fig.7(b), the operator path command (a red trajectory) collides with an green obstacle which is the latest environment data. However, it clearly can be confirmed that a com-
mand path is avoided an obstacle by the distortion compensation.

4.2. Simulation with Experimental measurement data

Another simulation result is shown in Fig.9. In this simulation, distance data was measured by a real stereo camera sensor which has 1.7[%] measurement error. Image data (a) and (b) were measured on the start point, and the point of 140cm from the start point. Fig.9(c) is a result of the command data compensation. Here, red boxes and belt were created at the start point, and yellow boxes are the latest measurement data at the point of 140 [cm]. The red belt crosses over a yellow obstacle which is the latest data. In this simulation, the compensated trajectory, a yellow belt, could also avoid from objects.

4.3. Simulation Result

A continuous and long-range simulation result is shown in Fig.10. It simulated the command data compensation, the object selection for the distortion compensation matrix, and a path tracking of a rover, under a distance error of 10% every 1[m]. The rover is a blue box located in the center of the red circle, and it is going to the up side. The triangle in the front of the rover is a camera sight, which has 60[degree]. The start point is (X:0.0, Y:0.0), and the goal point is (X: 5.0,Y:-0.5). Light blue boxes are obstacles which have been measured in the past of Td [sec], and the position data of the obstacles have

\[
A = \begin{pmatrix}
0.9942 & -0.1137 \\
0.9784 & 1.8642 \\
-0.0473 & -0.0132
\end{pmatrix}
\]

(a) At Start Point (b) At 140[cm] point

(c) Trajectory of Rover

Fig. 9 Simulation Results with Experimental data

a distance error. Red and blue lines are path commands which are tracked by a rover. Red line is a old path data based on previous map data, and blue line is the latest path data compensated with the latest map data. As shown in Fig.11, the rover could avoid obstacles without any collisions and any corrections by human operator, using trajectory data based on old map data.
5. Conclusion

The science on the moon has required the wide area investigation. But it is difficult to realize a long driving in an environment with communication delay. One of the solutions is Tele-drive system with a virtual world simulator. However, we have a difference between environmental map data of an operator and a rover, because of time-delay. This difference makes a reliability of command path lower.

In this paper, we proposed Tele-driving method with Command Data Compensation (CDC), for a long driving. The CDC is a kind of mapping to compensate a distortion of a space, and compensates command data according to the latest environmental data measured by a rover. As a result, the reliability of the command path is improved. We confirmed the effectiveness of CDC by some simulations. In the near future, we have to discuss the design of parameters for CDC and an operation way of proposed tele-driving system. Evaluations of those are also future works.

Reference