2007 ISAS 17th Workshop on
Astrodynamics and Flight Mechanics

Path Compensation and Hierarchical Autonomous Functions for Long Range Exploration Rover

*Yasuharu Kunii, ** Takashi Kubota

*Chuo University, ** Institute of Space and Astronautical Science, JAXA

Abstract : In such operation environments with long communication time delay as the moon or planets, it is difficult to compose a closed loop control between a master and a slave system. A new scheme is required to achieve the stability for tele-operation. This paper discusses and evaluates the proposed tele-operational driving system based on human machine cooperation that consists of global and local path-planning for long range traversability. The operator can command any desired path as a sequence of waypoints by using a 3D terrain model measured as DEM by the on-board sensors of a rover. The data are transmitted to the ground and evaluated to obtain a dangerousness map. To cope with an unknown obstacle, a conventional autonomous path-planning algorithm is applied to the interval between waypoints. In addition, a rover continuously updates its knowledge about the environment. By continuously recalculating the difference between the original terrain data used for initial path generation on the ground and the most recent data acquired by the rover, waypoints compensation can be achieved. Therefore, a rover has to compensate waypoints by using the latest measurement data which would be more reliable than the previous data, for corresponding to the difference automatically. Here, the difference is compensated by using a distortion compensation matrix which is the mapping between the old and new terrain data sets. This paper shows the simulation and experimental results and also its evaluation results by using the rover test-bed.

Keywords : Lunar or Planetary Exploration, Long Range Explorer, Tele-driving, Path Compensation.

惑星探査ローバにおける自律機能の階層化と指令軌道の補正

* 國井 康晴 # 久保田 孝

*中央大学, #宇宙航空研究開発機構

摘要： 月惑星表面移動探査では，ローバと呼ばれる移動ロボットを用いて，さまざまな観測を行うことが求められる．月惑星探査では事前に詳細な環境情報を得ることは難しく，活動環境は基本的に未知自然環境となる．操縦者による直接遠隔システムは，もちろん基本的な方法であるが，限られたリソースで遠隔操縦を行うためには，安全性および効率性の点で得策ではなく，ある程度の自律機能が必要である．そこで自律機能と操縦者による遠隔制御を融合した人間機械協調型の遠隔操縦システムが有効となる．本発表では，ローバの操縦システムにおいて操縦者を頂点に自律機能の階層化を行い，人間と操縦者の能力的適性を踏まえた上で役割分担を行うことで，未知の自然環境において効率的に移動するシステムを提案する．また特に操縦者の設定した指令軌道の環境への適応アルゴリズム（補正アルゴリム）に関して議論する．さらに本手法を実験により評価する．

1. Intoduction

In 1970, the first unmanned mobile explorer called Lunokhod has just knocked on the door of the solar exploration. As the next stage of planetary missions, Sojourner explored Mars in 1997 and MERs have moved and explored the surface of Mars these days [1][2][3]. This is just the beginning of a new era of planetary surface explorations by using a rover for engineering and scientific applications. Toward the next step, this paper discusses and solves a lot of research subjects on future exploration missions. In the near future, an efficient tele-driving scheme is required for long range traversability on planetary surface [4][5][6].

In such operation environments with long communication time delay as the moon or planets in space, it is difficult to compose a closed loop control structure between a master and a slave system. A new scheme to achieve the stability is thus necessary. The supervisory control system might be one of the solutions. A high-level supervisory control system also demands higher system performances, such as computational power and onboard sensors. In many cases, however, actual space systems have difficulties to install computers with high performance and onboard sensors, due to the problems of the harsh environmental system requirements, the weight controls for equipments, etc. Therefore, high-level autonomy cannot be expected on such a system, but the system can be acceptable, which is based on human direct and continuous tele-operational control with some low-level intelligence on the rover [6][7].

This paper proposes a tele-drive system with human machine cooperation, which consists of global and local path planning for long range traversability. The operator can command any desired path as a sequence of waypoints by using a 3D terrain model. 3D terrain model is obtained as DEM by an on-board sensor of a rover. The terrain data is transmitted to the ground station and also evaluated by the ground station computer. Then a dangerousness map is build. In order to react to and avoid an unknown obstacle, a conventional autonomous path-planning algorithm is applied to the path between one waypoint and the next waypoint. On the other hand, the measurement data of some area is supposed to be more reliable, when a rover is getting closer to this area. However, the rover calculates the difference between terrain data sets used for initial path planning by the operator and data sets acquired by the on-board sensors of the rover. This means that the trajectory by waypoints is going to collide to an obstacle because of the difference. Therefore, the proposed method compensates waypoints by the latest measurement data, to correspond to the difference automatically. Here, the difference is assumed as a distortion of data set, and also is compensated by using a distortion compensation matrix which is the mapping between the old and new terrain data.

In Section 2, the proposed tele-driving system is discussed along with the command path compensation algorithm. The simulation and experimental results and their evaluations are conducted in Section 3 and Section 4, by using the rover test-bed called Micro-5. Micro-5 has a five-wheeled rover with a passive suspension and a gimbal sensor mast as shown in Fig.1.

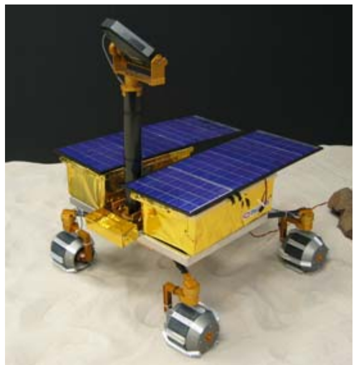

Figure 1 Rover Test-bed: Micro5-05

2. Cooperative Tele-driving System

2.1 Tele-driving System for Planetary Rover

In the case of a remote environment, some time-delay occurs between a master and a slave system due to the distance and the limited capacity of communication bandwidth. It is thus difficult to compose a closed loop control structure between the master and the slave system. Conventional tele-driving methods use some strange behavior called "Move & Wait" for operation of a rover, because of the time-delay. A rover has to wait for commands while the operator's planning the path. That requires careful consideration and as a consequence, that causes time consumption. Moreover, to avoid collision between the waypoint path and obstacles, a rover requests the operator to regenerate the waypoint path, which causes further delay until a new path data is received. Therefore, a new tele-driving scheme is necessary for safe, efficient and continuous driving of the rover, which should be a low-level intelligence that can understand human intentions in the operator's path command for obstacle avoidance [8][9].

Here, a human machine cooperative tele-drive system is discussed, consisting of a global and a local path planning for long range traversability as shown in Fig.2. The operator can create any desired command-path as a sequence of waypoints by using a 3D terrain model obtained as DEM data by an on-board sensor. Those data are transmitted to the ground station. A dangerousness map is then built using the received terrain data. However, the measured terrain model may include some errors and cause some problems. For example, generally, data measured by a sensor has proportional errors depending on the distance from a sensor to a measured target, and unknown obstacles might be found on the way of the path, because of an occlusion problem of sensors such as a stereo camera. Of course, a rover itself also causes position estimation errors and dead reckoning errors, because of slips of wheels etc. For corresponding to an unknown obstacle, a conventional autonomous path planning algorithm is one of solutions, and it can be applied for a short range path planning between each waypoint (Fig.2).

On the other hand, a rover is continuously updating the environment data set, and calculates the difference between original terrain data sets used for initial path planning by the operator and the data sets acquired by the on-board sensors of the rover. The original path may indicate the rover to follow a trajectory that might cause a collision to obstacles, due to the difference between the distorted original and the more accurate acquired data sets. Therefore, the proposed scheme compensates waypoints by using the latest measurement data which would be more reliable than the previous data sets. This is because the measurement data of a certain area is more reliable, when a rover is getting closer to that area. Here, assume that the difference between those terrain maps is the distortion between data sets, and the path would be compensated by using a distortion compensation matrix which is the mapping between the old and new terrain data sets. This command path compensation and its compensation matrix will be mentioned in the next subsection.

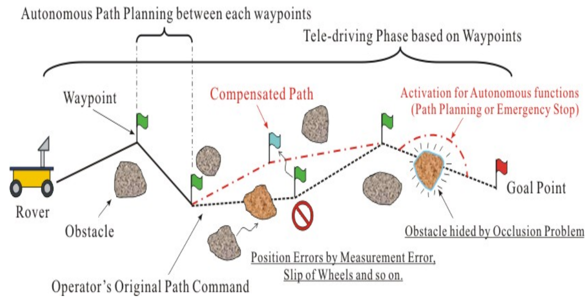

Figure 2 Tele-Driving System for Exploration

2.2 Command path Data Compensation

A DEM is a 2 dimensional scalar field with elevation values in each position *(x, y)*, according to the terrain elevation *z*. The map data distortion is due to the measurement error and the position estimation error of a rover, and cannot be calculated using only one parameter and in many cases it is also non-linear. The compensation of 3D non-linear distortion, however, makes the on-board algorithm of a rover more complicated. Therefore, this paper assumes that the distortion has two dimensional and linear properties, and a compensation algorithm of the camera lens is applied on the compensation. The Command path Data Compensation (CDC) transformation is given by

$$\bar{X} = XA, \tag{1}$$

,where the rows of the matrix $\boldsymbol{X}$ consistes of position data sets of landmarks(LMs) in the old terrain data, $\bar{\boldsymbol{X}}$ is also LM data of the latest environmental data, and $\boldsymbol{A}$ is the distortion compensation matrix. Actually, only three pairs of the LM data sets ($\boldsymbol{X}$ and $\bar{\boldsymbol{X}}$) are required for the acquisition of $\boldsymbol{A}$, if these measurement data have high accuracy. However, measurement data usually includes any nonlinear noise because of measurement errors and position estimation errors of a rover. So, a sufficient number of LM sets are required to obtain a suitable linear solution by using least mean square techniques.

Here the pseudo-inverse of *X* is used to obtain the matrix *A*, defined as

$$X^{+} = [X^{T} X]^{-1} X^{T}. \tag{2}$$

Eq.(2) is applied on Eq.1 and the matrix $\boldsymbol{A}$ is given as

$$A = X^{+} \bar{X}. \tag{3}$$

Finally, the new compensated waypoint set is obtained from

$$Wp_{new} = Wp_{old} A \,, \tag{4}$$

,where Wp_{old} is the waypoint data matrix created by the operator, and Wp_{new} is the compensated waypoint data matrix.

3. Simulation Study

3.1 Command Data Compensation

Figure 3 shows simulation results of Command Data Compensation in the case of static state. Here, red boxes are obstacles measured as LMs in the past, and green boxes are the latest positions of LMs, and the red line in Fig.4 (a, b) indicates the operator's path command, and the blue line in (b) is the compensated data. Wide lines in (c) are the areas covered by the rover when passing along the trajectories (pink: the commanded path, blue: compensated path). The matrix ***A*** is given on the right hand side of (c). Each map data contains 10[%] errors, which is proportional to the distance from the rover. Though, in Fig.4 (b) the operator's command path (the red trajectory) collides with a green obstacle, it can clearly be confirmed that the blue compensated path avoids an obstacle after applying the distortion compensation algorithm, which shows the effectiveness of the proposed CDC algorithm.

(a) Command path (b) Compensated path

(c) Trajectory

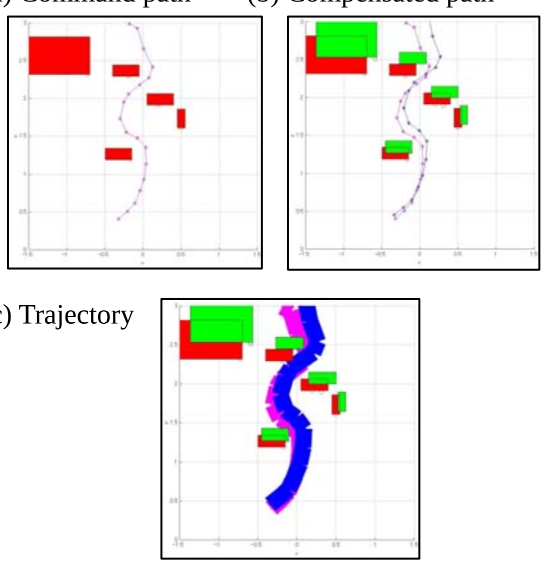

Figure 3 Simulation Results

3.2 Long Range Traversability

Simulation results of the continuous and long-range tele-driving are shown in Fig.4. The on-board sensor randomly has 10[%] of measurement error, proportional to the distance between a rover and each LM. The measurement area of the sensor is 10[m] long and 90[degree] wide. The slip rate is 10[%], proportional to the movement length of the rover. A rover measures the position of LMs and compensates the given path, at each waypoint. A rover is instructed to move on the blue curve, which is the original commanded path, as shown in Fig.4 (a). In Fig.4 (a), the rover is expressed as the blue box initially located at the origin. In this simulation, the length of the command path is more than 20[m] at a time.

In Fig.4 (b)-(e), the rover is located at the center of the circle which indicates the sensing range of the on-board sensor. The two black lines indicate the field of view of the sensor. Black lined boxes are the obstacles at their real positions, and boxes which are dotted and colored, indicate positions of measured obstacles. The green curve indicates the trace of the rover without any compensation method, and the rover is shown as the green box on the top of this curve.

The rover on the compensated path is indicated by a series of red boxes over the red curve along the compensated motion path. The pink curve means a predicted and traveled result at this time. Finally, the rover is safely following the trajectory to reach the goal waypoint. In the final position of the rover, the distance from the goal point is defined as a final error. CDC tele-driving has proved to yield lower errors than conventional simple methods because of the efficiency of the proposed algorithm.

Simple performance evaluations of CDC tele-driving against the communication time delay are shown in Fig.5 and Table 1. The traveling distances by each tele-driving method are decided, and the conventional method "Move & Wait" is inefficient because of the time waste due to the transmission of the operator's commands. The differences of the efficiency percentage by each sensing range are indicated in Table.1, which also proves the high performance of the proposed CDC tele-driving algorithm.

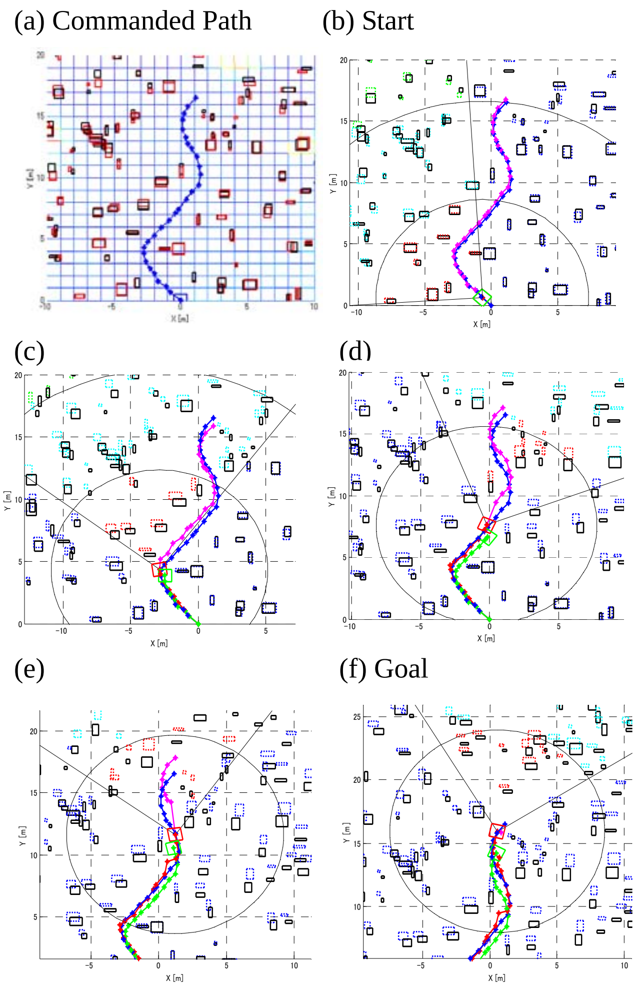

Figure 4 Simulation Results of Path Tracking

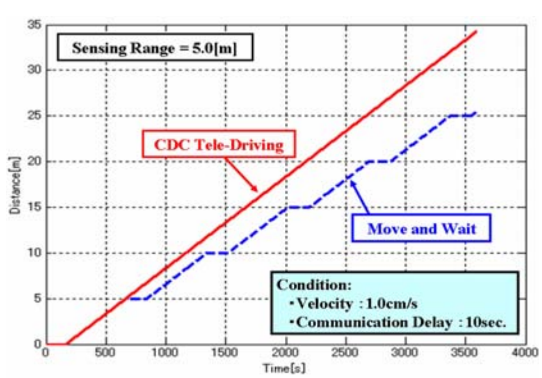

Figure 5 Performance Comparison

Table 1. Traversable Performance Evaluation

Sensing Range [m]	3	5	10
CDC Tele-driving[m]	34.95	34.35	32.85
Move & Wait(m&w)[m]	27.00	26.60	26.75
(CDC) / (m&w) [%]	129.44	129.14	122.80

3. Feature Landmark Selection

3.1 Command Data Compensation

During the path compensation process, the path might be changed beyond expectations, because measurement error on each Land Mark(*LM*) is uneven and a larger error has more influence on the compensated path. Therefore, feature points for the compensation matrix should be chosen from *LM*s, by considering the influence on the movement of the rover, as follows:

1. *LM*s that are near to the rover.
2. *LM*s that may possibly collide with the rover.
3. *LM*s that have a proven reliability based on measurement history.

3.2 LM Selection based on Area

First of all, *LM*s are chosen from the existence area shown in Fig.6, and than selected *LM*s are evaluated by the three criteria of distance, size and reliability. Figure 6 shows the structure of areas used for *LM* selection. *LM*s are selected from Area-1 & 2, and *LM*s in Area-1 have a higher priority. If a certain *LM* enters to Area-1, it is measured with high precision and is registered as a reliable *LM* in the measurement history list.

3.3 LM Selection based on Weight Function

3.3.1 Based on Distance from Rover

The distance from a rover is one of the most important factors, because measurement error is generally increasing by the distance from a sensor, and also a *LM* closer to the rover has a higher risk of collision, and thus is considered to be more dangerous. For example, a stereo imaging sensor has an error proportional to the square of the distance from the sensor to the measured target. Therefore, the reliability of *LM* is in inverse proportion to the distance. Let the distance from the rover to *LM* i

be l_i ($i = 3 \cdots m$), and the weight parameter w_i be defined as $w_i = l_i^2$ in the case of the stereo imaging sensor. The weight matrix L is given as

$$L_{m\times m} = diag\left(w_1^{-1}, w_2^{-1}, \ldots, w_m^{-1}\right) \qquad (5)$$

,where m is the maximum number of feature *LMs*.

3.3.2 Based on Size of Obstacles

In the sensor-acquired data set, each *LM* is represented in a certain area due to the size and the measurement error. Therefore, the size of the *LM* should also be considered for the *LM* selection. Here, the weight matrix S is given using the ratio of the size s_i of each *LM* as

$$S_{m\times m} = \left(\sum_{i=1}^{m} s_i\right)^{-1} diag\left(s_1, \ldots, s_m\right) \qquad (6)$$

3.3.3 Based on Reliability of Position

Once *LM* goes out of the sensing range, the uncertainty of measured *LM* position is increasing. It can be said that *LM*s kept being measured are more reliable. So it is necessary to use the *LMs*, which the rover has as much recent measurement data as possible. The reliability of an *LM* can be evaluated by using the passed distance l_{r_i} of the rover from the point where the *LM* had been measured for the last time. To select reliable *LMs* from the list, the weighting matrix H is introduced such that

$$H_{m\times m} = \left(\sum_{i=1}^{m} l_{r\_i}\right)^{-1} diag\left(l_{r\_1}^{-1}, l_{r\_2}^{-1}, \ldots, l_{r\_i}^{-1}\right) \qquad (7)$$

3.3.4 CDC by using Selected Landmark

By using the above mentioned weight matrices, the total weight matrix for CDC is defined as

$$W_{m\times m} = \beta_1 L_{m\times m} + \beta_2 S_{m\times m} + \beta_3 H_{m\times m} \qquad (8)$$

,where β_1, β_2 and β_3 are arbitrary design parameters. This weight matrix W is applied on Eq.(1), and the improved path compensation matrix is given as

$$W\,\overline{X} = W\,X\,A' \qquad (9)$$

The improved compensation matrix A' is derived as

$$A' = P^{+}\left(W\,\overline{X}\right) \qquad (10)$$

,where the matrix P is defined as $P=WX$ and P^{+} is the pseudo-inverse matrix of P. Finally, Eq.(10) is applied on Eq.(2) and the improved compensated way points are obtained.

4. Experimental Results

Experiments for tele-driving are conducted by using the developed rover test-bed and the proposed control system with a command path data compensation algorithm. Figure 6 shows the developed rover and the scenery of tele-driving experimental setup in the indoor rover yard. Rover yard consists of sand and several rocks as obstacles, and has a rectangular shape of 4 x 8 meters. Figure 7 shows a control GUI window. The rover test-bed can communicate with the control station by using wireless LAN, and the rover is operated by using the GUI window (Fig.7). To acquire terrain data as DEM, the stereo camera unit on the top of the sensor mast in the middle of the rover is used. Figure 8 indicates the measurement terrain data sensed by the camera unit. Obstacles are recognized from the obtained DEM data, and then the operator considers, plans and decides a path by choosing a series of way-points while observing the DEM image on the GUI. The generated way-points are finally transmitted to the rover.

Figure 6 Indoor Rover Yard

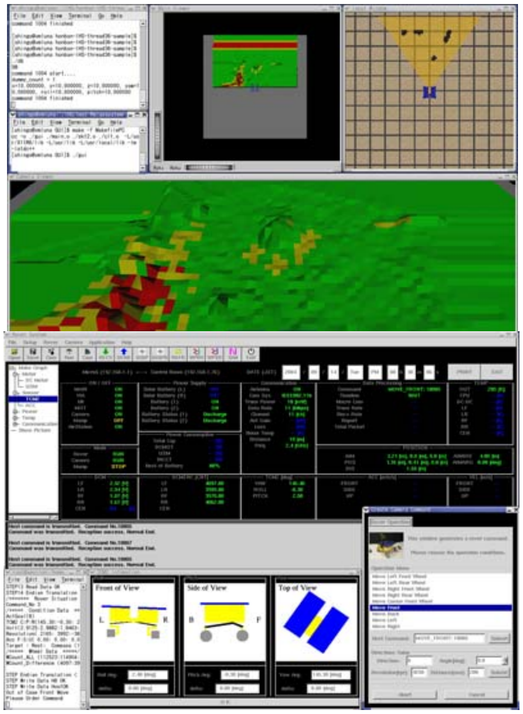

Figure 7 GUI Windows for Rover Control

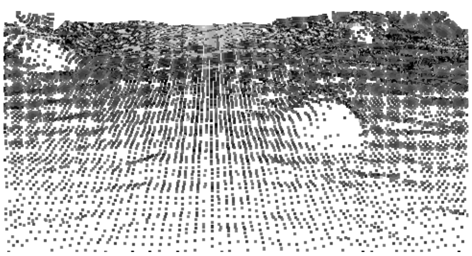

Figure 8 Terrain Map

Figure 9 shows the experimental results. The blue line indicates a command path made by the operator, and the green line is the path without any compensation. The red line in (a) and the pink line in (b) are compensated by CDC using all LMs. On the other hand, the red line in (b) is compensated by CDC with selected LMs. Here, trajectory is measured by using a polhemus sensor. Though collisions are caused on green lines, compensated paths are safely passed to the goal. In addition, the LM selection works very well as shown in Fig.9 (b). In these experiments, though the rover has 23[%] error of slip of wheels, the rover safely completed the mission to reach the goal. Therefore, the effectiveness of the proposed algorithm is confirmed.

(a)

(b)

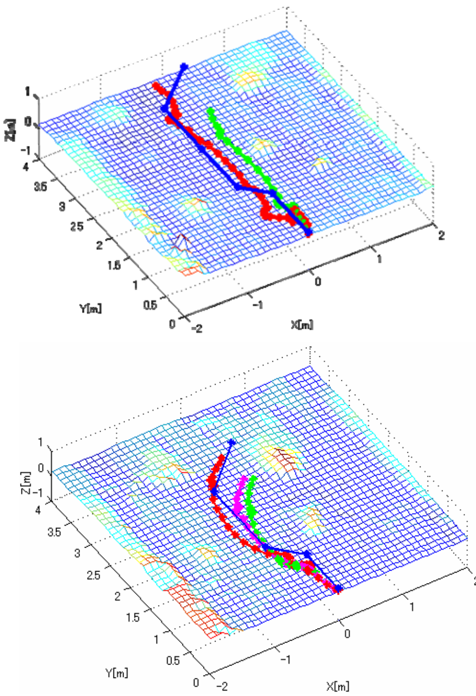

Figure 9 Experimental Results

5. Conclusions

The scientific mission on the moon has required the wide area of investigations. However it is difficult to realize a long driving in an environment with communication delay during the limited mission period. One of the solutions is the introduction of tele-drive systems with a virtual world simulator. Even if those systems are introduced, there is a problem to have a difference between environmental map data of an operator and a rover. This difference makes a reliability of command path lower. This paper proposed a new tele-driving method with Command Data Compensation (CDC), for a long driving. The proposed 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. The effectiveness of the proposed CDC has been confirmed by some simulations and experiments by using a developed rover test-bed.

References

[1]http://www.planetary.org/rrgtm/tpr_rover-rus_communications.html

[2] R.Volpe, J.Balaram, T.Ohm, R.Ivlev: "The Rocky 7 Mars Rover Prototype," Proc. of Int. Conf. on Intelligent Robot and Systems, pp.1558-1564, 1996.

[3] R.Volpe: "Rover Functional Autonomy Development for the Mars Mobile Science Laboratory," Proc. of the 2003 IEEE Aerospace Conf., 2003.

[4] R.Simmons, L.Henricksen, L.Chrisman, G.Whelan: "Obstacle Avoidance and Safeguarding for a Lunar Rover," Proc. of AIAA Forum on Advanced Developments in Space Robotics, 1996.

[5] E.Krotkov, R.Simmons, F.Cozman, S.Koenig: "Safeguarded Teleoperation for Lunar Rovers," Proc. of SAE 26th Int. Conf. on Enviromental Systems, SAE paper # 961585, 1996.

[6] J.L.Loch,D.Desai: "Moose on the Loose: Toward Extended Mission Autonomy for Robotic Exploration of Planetary Surface", Proc. of ICAR'93, pp.97-101,1993.

[7] G.Giralt: "Remote Intervention Robot Autonomy and Real World Application Cases", Proc. of IEEE Int. Conf. on R&A, pp.541-547, 1993.

[8] R.Chatila, R.Alami, S.Lacroix, J.Perret, C.Proust: "Planet Exploration by Robots: From Mission Planning to Autonomous Navigation", Proc. of ICAR'93, pp.91-96, 1993.

[9] L. Matthies, E. Gat, R. Harrison, B. Wilcox, R. Volpe, and T. Litwin: "Mars Microrover Navigation: Performance Evaluation and Enhancement.", Autonomous Robots Journal, special issue on Autonomous Vehicles for Planetary Exploration, Volume 2(4), pp. 291-312, 1995.