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Tele-Driving System for Nonstop Traveling of Lunar Rover and Its Field Experiment

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Abstract

In this paper, we show how the system of achieve nonstop traveling, works and its field experiment. In this system, the rover in the remote site synchronously move with some constant delay from the rover in the local site. The system was actually built and experimented by test-bed. The test-bed in the remote site was able to run without feeling an influence of time delay, bandwidth limitation of communication. Therefore, the validity of this system was able to be proved.

1. Introduction

The rover in future Moon mission is expected to traverse for kilometer-range during two-weeks mission term. Neither direct remote control nor ordinary tele-command control has enough performance to travel such long distance in the short term. Because some reasons are considered as follows. The direct remote control must not be functioned because of narrow communication bandwidth. The delay of propagation of communication by the distance between the Moon and the Earth is only 1.3 seconds, but the delay by narrow bandwidth would be no less than 10s of seconds. On the other hand, the ordinary tele-command control has a problem that the rover *must* stop to wait receiving commands from the Earth, e.g., the path data that planned on the Earth and the rover should playback on the Moon surface.

In order to travel long distance in the short term, therefore, increasing efficiency of moving is essential. Increasing efficiency of moving means the rover should not stop for waiting to receive commands sent from the Earth. [1-5]

2. Tele-Driving System for Nonstop Traveling

2.1 System Architecture

The proposed tele-driving system shown in Fig. 1 consists of the remote (Moon) site, and the local (Earth) site. In the local site, there are a virtual world and its predictive display. The virtual world is modeled by the real rover with geographical information, mechanics of soil (slippage of wheels), etc., of the Moon surface. An operator on the Earth "drives" – actually just commands to move to the next

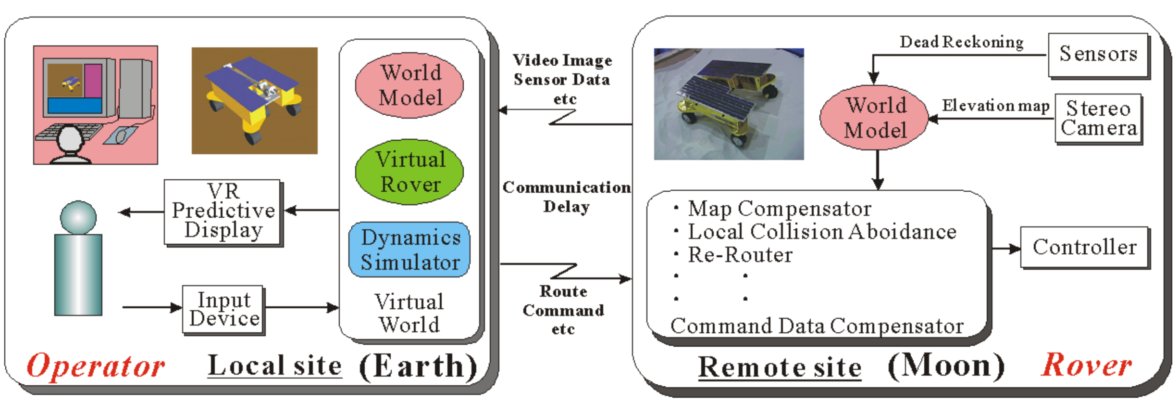


Fig.1 Architecture of Tele-Driving System for Nonstop Traveling

way point to – the virtual rover in the local site. Some of the key data of the simulation are sent to the real rover as tele-commands. In the remote site, the real rover tries to playback the results of simulation sent from the Earth. In this system, the real rover should synchronously move with some constant delay from the virtual rover on the Earth. If the results of simulation were not able to playback on the Moon because the simulation were not accurate enough, the real rover would try to compensate the commands so as to reach to the way point destination on time.

The real rover measures geographical information and mechanics of soil of surroundings during traverse, and she sends them back to the local site. Since these data are used for creating and updating the virtual world on the local site, the data must be arrived to the local site before they would be used. Thus, the real rover measures geographical information in the area where the rover would go minutes after. The data of mechanics (slippage) of soil should be estimated from those sampled where the rover is now on.

2.2 Synchronization Strategy

Figure 2 shows a time chart when the proposed tele-driving system performs a typical operation. In the time chart, time delay caused of the distance is shown as "Td". The Td should be set at least the time taken between the Earth and the Moon in one way (approximately 1.3 seconds). Actually, it is supposed to take more because of circuitry distance. The severe bandwidth limitation also exists because the long-range rover has to communicate directory to the local site on the Earth. So the time delay cause of bandwidth limitation is shown as Tb. The system works as following schemes. (1) At first, the real rover on the moon measures geographical information to create the world model which mainly consists of mechanics of soil, and the map where the rover could go 2Td+Tb after. The information is transmitted to the local site as soon as possible. Relative or absolute position of the rover should also be measured and transmitted at least 2Td before moving. Relative or absolute position of the rover should also be measured, simultaneously. These data are transmitted to the local site. (2) On the local site, the virtual world is created or updated with the data sent from the real rover. An operator decides positions of way points (WPs) where the rover should go, and points them out on the predictive display. The virtual rover begins to move on the surface of the virtual world in the direction of the next way point. The data of pointed WPs are transmitted to the real rover. (3) The real rover begins to move on the Moon when the first datum of WP is received from the local site. The real rover tries to move the same way such that the virtual rover has done. The real rover is measuring geographical information of the surface continuously where she would go 2Td+Tb after as same as section (1) during traverse, and sends them back to the ground successively. (4) The world model in the virtual

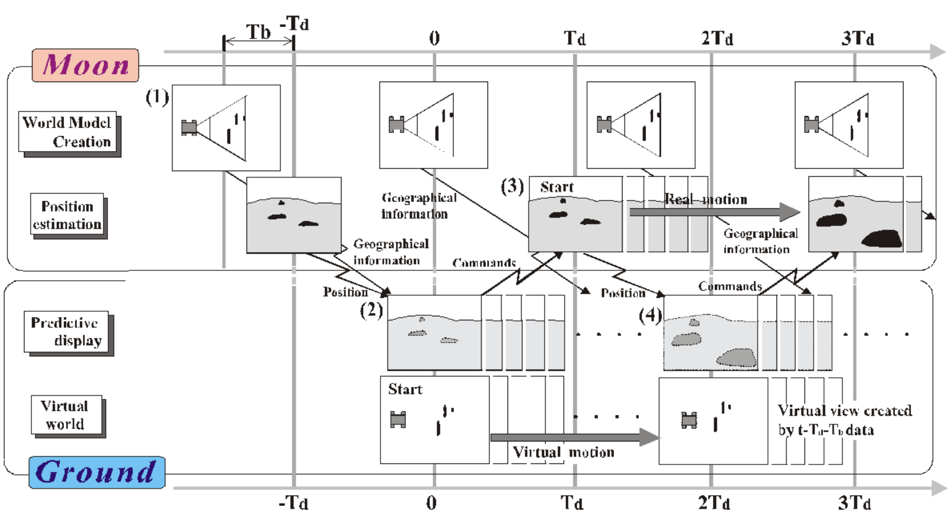


Fig. 2 Time Chart of the Tele-Driving System. The real rover playbacks the results of simulation with constant time delay. For ease to explanation, the time-delays of both up and down links are shown as 'Td', but they do not need the same values.

world is updated and extended with the geographical information data sent from the real rover. The operator decides the next WPs again and points them out on the predictive display.

By repeating the process of (3) and (4), the virtual and the real rover moves to a series of WPs without be interrupted. The WPs should be decided by the operator so as not to step the virtual rover. The real rover must not stop unless the command is not executable because of unexpected happening. If the time delay changed irregularly, the system would be available by setting both Td and Tb appropriate.

3. Field Experiment

In order to verify whether the system works correctly to drive a real rover or not, field experiments were carried out. Figure 3 shows the system configuration for the field experiment.

In the local site, the system consists of a virtual world for managing the world model of the Moon environment and the virtual rover, the user interface for observing the virtual world and determining the WPs, a database for storing the various data, and a data management system. All data are transmitted and received through the data management system. The operator points the new WPs out on the predictive display, the WPs are sent to the autonomous navigation system of the virtual rover.

The remote site - which is the real rover - consists of sensors, actuators, and some control software modules. It creates a world model of its surroundings and estimates the position using the RSV system. Autonomous navigation system is the equivalent one in the virtual rover controls mobility system and navigates the rover itself. Other control subsystems can be installed such as an autonomous sampling system, and scientific measurement and analysis, if necessary. Mission manager subsystem communicates with local site, and deals with these software modules.

Time delay queue is introduced in between the remote and the local site in order to simulate the time delay and the bandwidth between the Earth and the Moon. Two FIFO buffers and real-time clock realize this queue.

3.1 Autonomous Navigation System

The autonomous navigation system has as follows:

Route Planner creates sub-goals between the WPs.
Path Planner creates a path between the sub-goals.
Low-level Controller controls to track the path.
Dynamic Simulator determines the rover's action.

The autonomous navigation systems in both the local and the remote site should be equivalent, because the real rover needs to know the simulation results in the local site. The system navigates and controls the vehicles with position data of the WPs. Therefore, small amount of data is needed to transmit to the real rover to behave as the same motion of the virtual rover. Actually, since the estimated errors between the world model and the real environment exist, the navigation system on the real rover has to compensate the difference between the results of the simulation and the

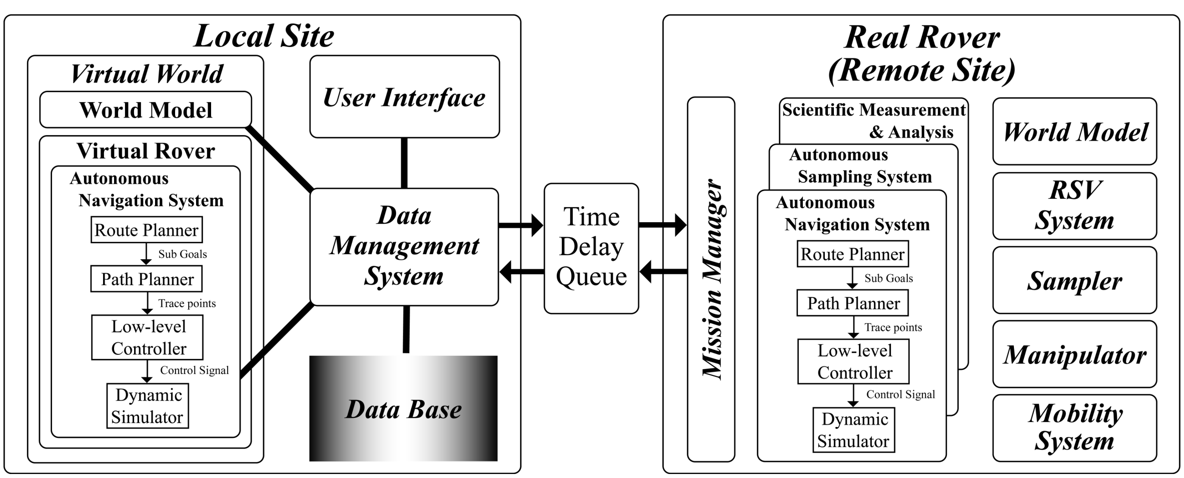


Fig. 3 System Configuration for Field Experiment

real motion by controlling velocity, replanning the path, and/or route.

3.2 Real-time Self-localizing Vision System

In order to the rover explores for long range, both her position and geographical information must be measured by herself in real-time, because the rover has to go out of the range of supervision of a landing module. The "Real-time Self-localizing Vision (RSV) System"[6] has been developed and introduced to the long-range rover for estimating its position and creating maps of surroundings by measuring geographical feature information. [7-9]

3.2.1 Self-localizing Algorithm

The RSV system based on the stereo vision technology measures its position by integrating the relative movement against surrounding features. In order to measure the relative movement, the RSV uses some remarkable technologies such as (I) automatic extraction of the new feature points from the captured image, (II) trigonometric measurement of relative positions of the feature points with the stereo vision, (III) rating the importance of the extracted feature points and tracking, and, (IV) 3DOF relative translation computation by trigonometric measurement of the feature points between before and after movement. Details of each technology are described as follows:

I. *Automatic extraction of the new feature points*

The images of the stereo vision consist of those captured by cameras set on the left and the right. The left image is defined as the master, and the right image is as the slave here after. At first, some feature points that have crisply colored texture are extracted from the master image. The feature points are registered as templates to use in the following schemes.

II. *Position measurement of the feature points*

The feature points corresponding to the registered templates are searched from the slave image by normalized correlation-based template matching method. Finding the parallax which is between the feature points on master and slave images the relative positions of feature points is equivalent to measuring by trigonometric measurement.

III. *Tracking and rating the feature points*

The tracking of the feature points extracted in section (I) is carried out at all times. When a point of them is lost or goes out of view, the new point should be extracted again automatically. Since attitude angles are used for calculating the movement, only one feature point is needed for (Details are explained in section 3.2.2). Therefore, the RSV system is very robust because it should be enough to track only one feature point, and the result of calculation can be reliable by applying statistics for many tracked points.

To choose points should be tracked among many extracted features, rating is carried out with correlation intensity of template matching, tracking duration, and distance between the feature and the system. The rates are also used for statistical calculation as mentioned above.

IV. *Computation of 3DOF relative translation*

3 DOF relative translation is calculated between before and after movement. The position after movement can be defined in the body coordinates system before movement, hence, all positions are defined in the initial body coordinates system. The calculation is carried out using three rotation angles of attitudes between before and after movement as shown in section 3.2.2.

3.2.2 Method of Using Attitude Angles

If 6 DOF of movement were calculated from only image information, at least four feature points' relative positions must be measured at all times. To keep calculating at least four positions in this case is actually very difficult, because these points must be scattered each other for being baseline elements of trigonometric measurement. Thus, the RSV system uses not only visual image but also attitude angles so as to calculate movement by tracking the only one point. Figure 4 shows the relation between the

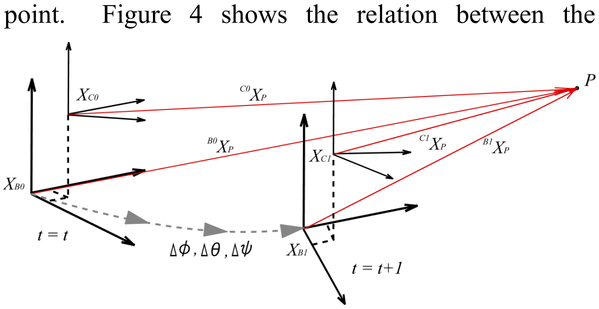


Fig.4 Transformation

coordinates systems before {0} and after {1} movement. Where subscript B shows the body coordinates of the rover, and C shows the camera coordinates. If change of attitude angles between before and after movement are measured as $(\Delta\phi, \Delta\theta, \Delta\varphi)$ translation movement (t_x, t_y, t_z) can be calculated as:

$$\begin{aligned}\left[t_x\ t_y\ t_z\ 0\right]^T &= \left[x_0\ y_0\ z_0\ 1\right]^T - \left[x_1\ y_1\ z_1\ 1\right]^T \\ &= {}^{B0}X_P - {}^{B0}_{B1}R\,{}^{B1}X_P \\ &= {}^{B0}_{C0}S\,{}^{C0}X_P - {}^{B0}_{B1}R\,{}^{B1}_{C1}S\,{}^{C1}X_P\end{aligned}$$

where, S is homogeneous transformation matrix, and R is rotation matrix.

3.3 Verification Experiment

The proposed tele-driving system is designed for operating a long-range lunar roving vehicle like "Micro5" as shown in Fig.5. [10] The Micro5 was constructed as a prototype for future Moon missions. For ease of examining effectiveness of the proposed system, we use a test-bed vehicle "Onion" constructed for sensing and navigation experiments as shown in Fig. 6. The Onion is equipped with equivalent sensors and processing units of the Micro5, e.g., the RSV system on the top of the mast for localization and map building, SH3 embedded RISC processors for control, navigation and communication, a "Super V Chip" DSP for vision processing. Narrow-band communication link is emulated by using 11Mbps spectrum-spread wireless LAN adapter.

Fig. 5 "Micro5" is The Lunar Rover with RSV system on the top of the mast.

In the field experiment, the time delay Td is set as 3 seconds. Bandwidth of the communication link between the Earth and the Moon is supposed to be 10kbps. If a size of geographical information datum per one point were 12 bytes, up to 100 positions of data could be transmitted in one second. Supposing a set of geographical information is associated from 200 points, the delay Tb should be 2 seconds.

Figure 7 shows the positions of the WPs used in the experiment. The WPs are pointed out by human operator, and are sent to the rover on the Moon step by step. Figure 8 shows some situations of the experiment (upper pictures) and predictive images of the virtual world built by the data from the Onion (lower images), respectively. The lower images (a)-(c) in Fig. 8 correspond to the upper pictures, respectively. Lines shown in the predictive display are connected route locus of the WPs.

Figure 9 shows trajectories of the real and the virtual rover, and created world model in each time step. The real rover follows the virtual rover's route with delay of 3 seconds, however, the real rover's

Fig.6 Test-bed "Onion" is a vehicle especially designed for sensing and navigation experiment.

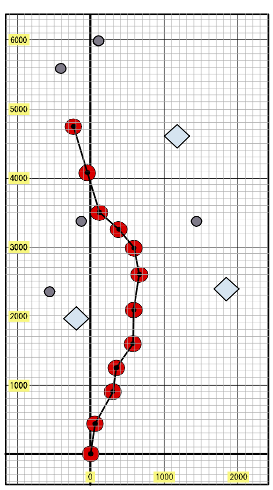
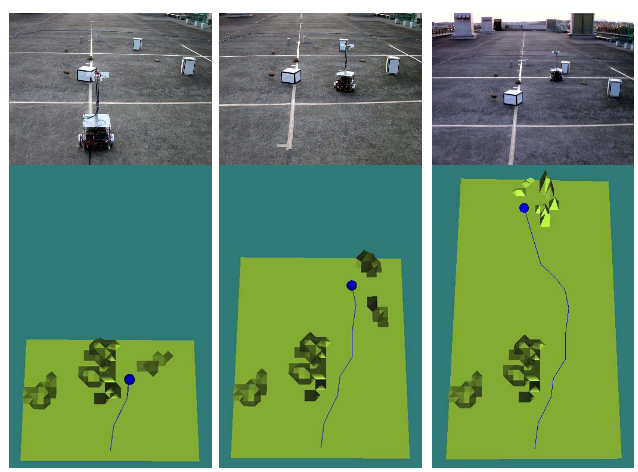
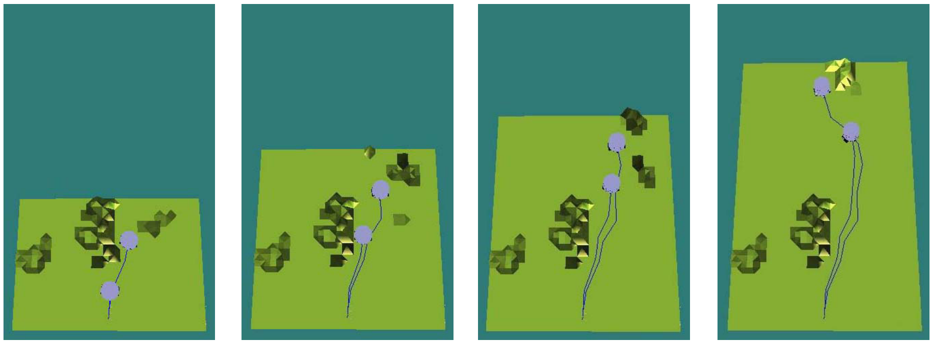


Fig.7 Way Points are pointed out on the predictive display by human operator, and are sent to the rover on the Moon step by step.



(a) t = 0 (b) t = 203.5 (c) t = 505.5

Fig.8 World Model and Way Point. The virtual world is rebuilt on the local site with the geographical information measured by the real rover, and it is shown on the predictive display.



(a) t = 79.5 (b) t = 140.0 (c) t = 212.5 (d) t = 307.5

Fig.9 The trajectories of both real and virtual rovers are shown in the virtual world.

movement is reflected on the display with delay of 6 seconds. Figure 10 shows the resulted trajectories of the rovers. It is noted that the locus of the real rover is odometry, because the odometry is the closest to the true value. The errors between the real and the virtual rover is mainly caused by the hardware limitation of the experimental model. Table 1 is the time chart shows the passage time of the real and the virtual rover by each way point. In the result of the experiment, the execution time is approximately 530 seconds.

When the experiment is performed by using the conventional "stop and go" scheme, it takes over 900 seconds in execution. Thus, almost 40% of time saving can be achieved by using the proposed "Tele-Driving System for Nonstop Traveling".

4. Conclusion

We proposed "Tele-Driving System for Nonstop Traveling" to run a rover in unknown environment without stopping in spite of the circumstance with time delay and limited bandwidth. The system successfully navigated a test-bed vehicle in a field experiment. Therefore, the rover in future moon mission could go far away from landing site where the detailed map is not measured beforehand during short mission term.

Table 1 Time Chart.

WP - Index	Passage time [sec]	
	Virtual	Real
Start	12.7	55.2
1	50.1	84.0
2	81.5	153.5
3	110.0	203.1
4	140.0	244.9
5	173.8	281.6
6	213.8	312.9
7	254.4	365.3
8	279.2	402.7
9	307.8	469.6
10	345.7	500.7
11	375.1	540.4

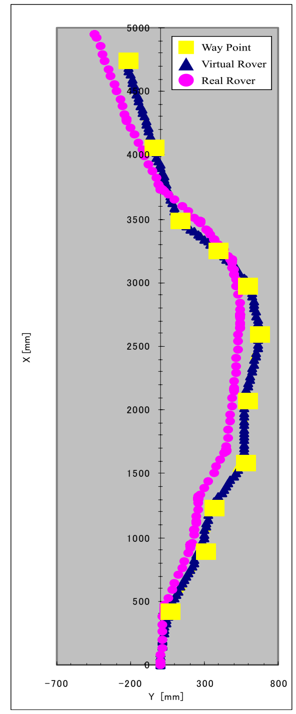


Fig.10 Trajectories of the rovers.

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