International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

Interim Report **IR-08-023**

Man-Machine Control of Space Robots under Uncertainty

Sayaka Kanata (sayaka.k@ky8.ecs.kyoto-u.ac.jp)

Approved by

Marek Makowski (marek@iiasa.ac.at)
Leader, Integrated Modeling Environment Project

October 2008

Foreword

This report describes the research the author did during her participation in the 2008 Young Scientists Summer Program (YSSP) with the Integrated Modeling Environment Project. The research documented in this report is a well defined part of the long-term research the author has been doing at her home institution. The long-term goal is to design a navigation strategy for a partly-autonomous robot operating on a small asteroid. The goal for the three months short Summer-period of the YSSP was to develop a model for robot's path design, and explore possibilities of applying multicriteria analysis of discrete alternatives to analyzing the model and thus supporting the operator in designing a path that reflects his/her preferences for trade-offs between conflicting objectives that measure a path quality.

The author has defined a model for representing the long-term goal. This model is composed of three submodels, one of them is the model supporting robot's-path design. The latter model has been developed in more detail than the other two, and a dedicated analysis method has been proposed, implemented, and tested. A proper support for analysis of this model is of a critical importance because a wrong robot's navigation is likely to result in a failure of an expensive space mission.

Analysis of trade-offs between conflicting objectives is a key problem in the robot's path design. To verify the proposed approach a large set of paths has been generated using actual data describing an asteroid. For supporting analysis of a large set of paths the author has been successfully using the MCAA (Multi-Criteria Analysis of Alternatives) tool developed at IIASA. The proposed structured approach to modeling complex navigation problems has therefore been proven to be effective, and provides a solid basis for development of the other two submodels.

One may wonder if and how the research on control of partly-autonomous space robots is related to the IIASA mission. The answer however is simple. Although the considered problem is not directly related to policy-making, it is closely related to our research agenda, and it is very important for our collaborators of the Kyoto University. Modeling methodology and technology developed at IIASA is applicable also to this problem, therefore it has been possible to exploit the synergy of the experience and needs. But also IIASA has gained from this case study. This application provided a test-bed for the modeling tools developed at IIASA. The preliminary analysis documented in this report shows that MCAA (originally developed for analysis of future energy technologies) can successfully be applied also to the path design problems. Since the MCAA is a Web-based application, therefore it is easily available for the author's future research.

Summing-up: the report documents a novel approach to solving an important class of problems, and illustrates synergies of interdisciplinary research.

Abstract

Control problem of space robots is characterized by several challenges. The first one is that the area is full of uncertainties due to lack of information. Another difficulty is task-sharing between an operator and a partly autonomous robot. Moreover, there are several constrains on the robot operations, including communication delay and an appropriate temperature at which robot can work.

Design of the robot's navigation should be based on consideration of trade-offs between several conflicting criteria, such as maximization of the robot safety, minimization of the energy consumption, maximization of the value of information collected by the robot during its movement.

Our research objective is to design man-machine interactive system, dealing with navigation problem of space robots. This paper focuses on the problem of path planning for small robot exploring a small asteroid. This problem is solved by an operator controlling the robot from Earth.

Keywords: navigation under uncertainty, multi-criteria analysis, space robots, man-machine cooperation, small planetary body

Acknowledgments

This report describes research done during my participation in the 2008 Young Scientists Summer Program (YSSP) with the Integrated Modeling Environment Project of the International Institute of Applied Systems Analysis, Laxenburg, Austria.

I would like to appreciate Dr. Marek Makowski of IIASA for his continuous support, encouragement and lots of advice on my research. I also acknowledge the usefulness of Multi-Criteria Analysis of Discrete Alternatives (MCAA), the Web-based tool developed by the Integrated Modeling Environment Project team. I would like to express my sincere gratitude to all the YSSPers and staff, especially Adam Kiczko, Shuo Liu and Dongling Zhang for their advice and hearty words.

My research has been partially sponsored by Japanese Ministry of Education, Culture, Sports, Science and Technology and I express my grateful thanks for that. I would also like to wish many thanks to Dr. Hiroaki Nakanishi of the Kyoto University for recommending me as YSSP participant and supporting my presentation-tasks in Japan during my participation in the YSSP. Finally, I wish to thank Prof. Tetsuo Sawaragi of the Kyoto University for supporting financially this important research.

About the Author

Sayaka Kanata graduated from the University of Tokyo with a master's degree in electro Engineering in March 2005. She has completed her master course at the Institute of Space and Astronautical Science (which is the central institute of Japan's space exploitation), where she worked on localization of robots on asteroids. Her scientific interests include artificial intelligence, autonomy and mobile robots.

She worked at ASAHI KASEI EMD in 2006 and she is currently a second year Ph.D. student at the Kyoto University, Mechanical Engineering and Science Department. Sayaka participated in the 2008 Young Scientists Summer Program (YSSP) with the Integrated Modeling Environment Project.

Contents

Man-Machine Control of Space Robots under Uncertainty

Sayaka Kanata (sayaka.k@ky8.ecs.kyoto-u.ac.jp)[*]

1 Introduction

Investigations into small planetary bodies such as comets and asteroids attract several groups of scientists recent years. In 2003, Japan had launched spacecraft Hayabusa to the asteroid Itokawa, whose maximum diameter is 600[m]. The spacecraft Hayabusa successfully touched down on the surface of the asteroid for the first time in the world [1].

The spacecraft Hayabusa carried a robot Minerva (Fig. 1), whose size is 0.1*0.1*0.1[m] and weight is 0.6[kg]. The robot is totally different from conventional robots on planets, such as Mars Exploration Rover, whose size is 1.5*2.3* 1.6[m], the weight is 180[kg], and has 6 wheels. Since the asteroid Itokawa has micro gravity, a robot on the surface cannot move by wheels. The scientists developed Minerva as a small hopping robot, which is specialized in the micro-gravity environment [2].

Another problem is that conventional methods of localization cannot be applied to small planetary bodies because their localization accuracy and range is insufficient for navigation. We proposed a method of localization using radio waves, which is efficient not only for large planets but also for small asteroids [3].

A space robot is a partly autonomous, i.e., an operator located on earth navigates the robot to a desired position. Navigation of a space robot has four difficulties. First difficulty is due to the area which is full of uncertainties. We have neither precise terrain map nor gravitational map of the investigated planetary body; the precise rotational motion of the body is also not known. These information can be acquired by the robot; therefore the navigation of a robot and correcting information are problems that have to dealt with simultaneously. Another difficulty is task-sharing between an operator and a partly autonomous robot. Moreover, navigation has to be designed through analysis of trade-offs between several conflicting criteria such as minimizing time to reach the goal, maximizing the safety of a robot, minimizing the energy consumption. These criteria usually cannot be satisfied at the same time; therefore one needs to solve a multi-criteria problem, this is the third difficulty. We also have to consider some constraints including communication delay between the investigated planetary body and the earth, and appropriate temperature for the electric devices.

Our research objective is to design a man-machine control system to help an operator, who is working on complex and time-dependent problem solving tasks. To achieve

[*]Kyoto University, Graduate School of Engineering, Department of Mechanical Engineering and Science, Kyoto, Japan.

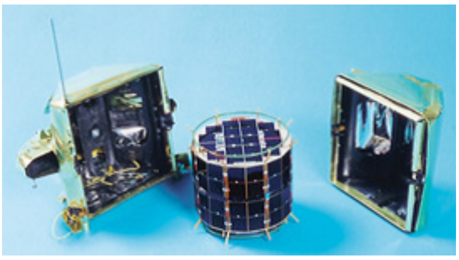

Fig. 1: Hopping robot MINERVA.

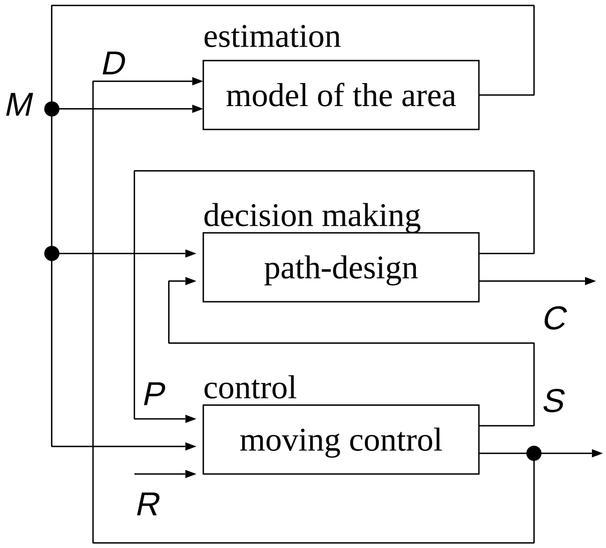

Fig. 2: Three models in navigation problem.

this goal we develop a navigation model, which is composed of three sub-models as illustrated in Fig. 2. First sub-model is a model of the area using collected data. Second sub-model is path-design by an operator using multi-criteria analysis. The last sub-model is autonomous movement of the robot. In 2nd chapter, we will explain each sub-model in detail. Then we will focus on the 2nd sub-model, path-design by an operator in 3rd chapter. 4th chapter shows simulation results using real data of asteroid Itokawa. Summary and conclusion of our research is in the 5th chapter.

2 Navigation Strategy

2.1 Control Overview

A robot on the surface of the investigated body does not only move toward a goal position but also stop for a certain period of time, whenever one of three reasons occur. First, it has to stop to save or charge the battery when it doesn't have enough energy to move. The second reason is because of the outside temperature. The temperature on the surface of the planetary body may increase over 100 [°C], and may decrease below 0 [°C]; In order to minimize the risk damage the robot its electric devices should be shut-down when the

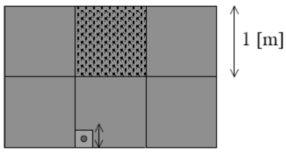

Fig. 3: Resolution of the model of the area and sensor range.

temperature is outside of a given range. The last reason is to reduce the uncertainties in position of the robot. The method of localization we have proposed [3] can reduce the ambiguities in robot's position, but its application requires the robot to stop for several hours. After reducing the position ambiguity, charging enough energy to move, and wait for the appropriate temperature to turn on the electric devices, the robot will move following the path designed by an operator.

A robot is partly autonomous and can move toward the designed goal position, avoiding obstacles detected by on-board sensors. However, the sensor range is limited that it may be trapped by concave obstacles. An operator on earth has to navigate the robot using detail information from on-board sensors. Thus, cooperation between an operator and a robot is required. Since the path for a robot should be considered in multiple points including the length, safety of the path, we regard a navigation problem of remote robot as a multi-criteria problem.

2.2 Model Specifications

We assume an operator on the earth, a robot on the surface of the investigated planetary body and an orbiter, which carried a robot to the surface. A robot can obtain terrain information and gravitational information from on-board sensors with high accuracy but the range is limited to its vicinity. An orbiter can obtain information of the whole surface of the investigated body but the resolution is low. The resolution of orbiter's information and the sensor range on a robot are illustrated in Fig. 3. The area is composed of a set of grids, and each of them is identified by a number and has parameters, which expresses the characteristics of the area.

As we mentioned already in the introduction, we propose a model of remote control composed of three sub-models as illustrated in Fig. 2. The first sub-model, a model of the area is an estimation problem, based on parameter learning. Parameters represent the characteristics of the terrain and their initial values are given by orbiter's information and they are modified based on information obtained by a robot after the locomotion.

The second sub-model is path-design by an operator with multi-criteria, which are explained later. Using the model of the area, an operator will design a path, considering with the ambiguity of the information and robot's state. Since the path-design depends on the resolution of model of the area, it would be specified as a set of way points. Each of way points has some margin because of the ambiguity in the model of the area.

A robot on the surface will move autonomously using the ambiguous path and the model of the area. This step is considered as the last sub-model: autonomous move and stop of a robot. A robot will move avoiding obstacles caught in sight, then stop at the last point and wait for a next command.

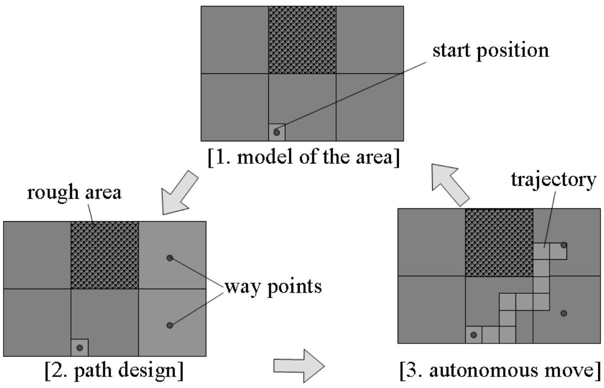

Fig. 4: Navigation steps.

Information of the regions within the range of the sensor along with the trajectory is used to modify the parameters of the area. Control of a robot will be described by repeating this cycle, "modify the parameters of the area", "path-design" and "autonomous move", as illustrated in Fig. 4.

After describing each sub-models in detail from next subsection, we will focus on the second stage, the path-planning problem of an operator.

2.3 Parameters and Variables

Sub-model1: Model of the area Inputs of the model of the area are data from on-board sensor and past parameters of the area, and output is modified parameters of the area.

$\mathcal{D} \in \Re^k$	(input)	data from on-board sensor
$\mathcal{M} \in \Re^{n\times\Lambda}$	(input/output)	parameters of the area

where k is number of sensor data, n is number of parameters in model of area, and Λ is total number of grids.

The initial parameters are defined by using orbiter's information and they are modified based on information obtained by a robot.

$$\mathcal{M}_{t+1}[i] = \begin{cases} f(\mathcal{D}_t[i]) & ([i] \in \mathcal{T} + \rho) \\ \mathcal{M}_t[i] & \text{(otherwise)} \end{cases} \tag{2.1}$$

where $\mathcal{T}$ denotes the trajectory of a robot and ρ is range of sensor.

Sub-model2: Path design by an operator Inputs of the path design are parameters of the area and state of a robot, and outputs are designed path and criteria for navigation.

$\mathcal{M} \in \Re^{n\times\Lambda}$	(input)	current model of area
$\mathcal{S} \in \Re^l$	(input)	current state of a robot
$\mathcal{P} \in \Re^N$	(output)	designed path
$\mathcal{C} \in \Re^m$	(output)	criteria

where l denotes the number of state of a robot, N is number of way points, $p_1, p_2, \cdots p_N$, each way point p_i is specified by grid number i and m is number of criteria.

Sub-model3: Autonomous move of a robot Inputs of this sub-model are parameters of the area, designed path, and sensor data. Outputs are current state of a robot and processed data of the area.

$\mathcal{P} \in \Re^{2p}$	(input)	designed path by an operator
$\mathcal{M} \in \Re^{n\times\Lambda}$	(input)	parameters of the area
$\mathcal{R} \in \Re^{s}$	(input)	raw data from on-board sensors
$\mathcal{D} \in \Re^{k}$	(output)	processed data
$\mathcal{S} \in \Re^{l}$	(output)	current state of a robot

where s is number of data which on-board sensors can detect.

The robot can move toward the way points and can avoid obstacles on its way. Obstacles are detected by on-board sensors, more precisely than sensors on the orbiter. However, the range is limited that concave obstacles may capture the robot. In such case, the operator has to navigate a robot using information by an orbiter and by a robot.

3 Multi Criteria Path Design

This paper focuses on the sub-model2, the path-design by an operator. The robot will move along the way points, designed by an operator, then will stop at the last point and wait for a next command. Thus alternatives considered in the multi-criteria analysis are composed of sets of such points. The operator's criteria $\mathcal{C}$ is composed of :

c[1]	$\Re$	obtainable information
c[2]	$\Re$	position ambiguity
c[3]	$\Re$	energy consumption
c[4]	$\Re$	device risk
c[5]	$\Re$	time efficiency

The first criterion, obtainable information, is the sum of expected value to visit along the path $\mathcal{P} = \{p_i\}(i = 1, \cdots N)$

$$c[1] = \sum_{i=1}^{N} a_{p_i}, \tag{3.1}$$

where a_i is value of information to visit the grid i.

The second criterion, position ambiguity, is the amount of uncertainty in position of a robot. The ambiguity will increase according with locomotion, and it can be reduced using landmarks within the sensor range.

$$c[2] = \sum_{i=0}^{N} \nu_{p_i} - \beta \sum_{i=1}^{N} l_{p_i} \tag{3.2}$$

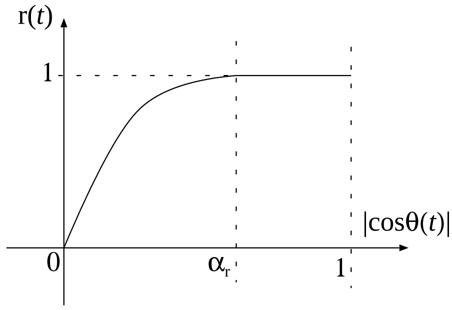

Fig. 5: Function $r(t)$: device risk.

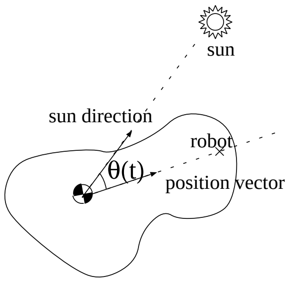

Fig. 6: Parameter definition of θ.

where ν_i is trace error, l_i is landmark density and $\beta > 0$ means weight.

The third criterion, energy consumption, is also defined as a sum of value of each grid,

$$c[3] = \sum_{i=1}^{N} e_{p_i}, \tag{3.3}$$

where e_i is energy consumption rate of grid i.

The forth criterion, device risk, is defined as

$$c[4] = \int_{t_s}^{t_e} r(t)dt, \tag{3.4}$$

where t_s and t_e are start and end of locomotion, respectively. Function $r(t)$ is defined using the angle θ between the robot's position from the center of gravity and the direction of the Sun, as illustrated in Fig. 6. Since the robot may move from night-region even to day-time region, we define function $r(t)$ as:

$$r(t) = \begin{cases} 1 & |\cos\theta(t)| > \alpha_r \\ -\left(\frac{|\cos\theta(t)|}{\alpha_r} - 1\right)^2 + 1 & |\cos\theta(t)| \le \alpha_r \end{cases}. \tag{3.5}$$

The function $r(t)$ is shown in Fig. 5, and the definition of angle θ is illustrated in Fig. 6.

The fifth criterion, time efficiency, means how effectively the operator navigates the robot. If the robot has more time to move safely, when it completed to follow the desired

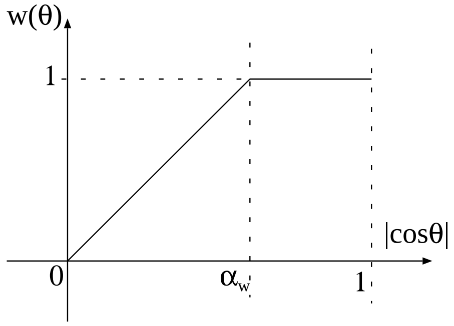

Fig. 7: Function $w(t)$: time efficiency.

way points, the operator should have designed longer path. We define function $w(\theta)$ as charted in Fig. 7.

$$c[5] = w(\theta(t_e)) = \begin{cases} 1 & |\cos\theta(t)| > \alpha_w \\ \dfrac{|\cos\theta(t_e)|}{\alpha_w} & |\cos\theta(t)| \le \alpha_w \end{cases} . \tag{3.6}$$

Summarize the above, the each grid has parameters $\mathcal{M}$, which describes characteristics of the area. $\mathcal{M}$ includes

a_i	$\Re$	value of information to visit
ν_i	$\Re$	trace error
e_i	$\Re$	energy consumption rate
l_i	$\Re$	density of landmarks

where i denotes grid number.

4 Validation of Proposed Model

To validate the proposed model of remote control, simulations have been conducted using the data of asteroid Itokawa. We used the shape model of the asteroid [4] presented by Gaskell [5]. The data has 49,152 facets in STL format, which specifies 3 vertices for each facet.

Decision making often requires analysis of large amounts of data and complex relations between Pareto efficient solutions. The MCAA tool provides both developers and users how to find a Pareto solution that matches best the user preferences . The user only has to set relative importance for each criteria, then one of Pareto solutions according to designed importance will be proposed with information about the distributions of criteria values.

4.1 Parameters Definitions

Information value at grid i is denoted by a parameter a_i, which is defined by

$$a_i = V[f_j] \cdot (f_i - E[f_j])^2 , \qquad j \in R_i(N_a), \tag{4.1}$$

where f is facet direction $\in \Re^3$, function $E[x]$ and $V[x]$ denote average and variance of x, respectively. Function $R(N)$ denotes a neighborhood region around grid i and N specifies the spread of the region. The variance of facet directions in a region reflects roughness of the region. Physical meaning of eq. (4.1) is that a rough region has higher information than smooth region and that the grid i has higher value to visit if it has unusual facet direction.

Energy consumption at grid i is denoted by parameter e_i and defined by:

$$e_i = V[f_j], \qquad j \in R_i(N_e). \tag{4.2}$$

Physical meaning of eq. (4.2) is that energy consumption increases with roughness of terrain.

Trace error at grid i is denoted by parameter ν_i and defined by:

$$\nu_i = V[f_j], \qquad j \in R_i(N_\nu). \tag{4.3}$$

Physical meaning of eq. (4.3) is that trace error increases with roughness of terrain.

Density of landmarks at grid i is denoted by parameter l_i and defined by:

$$l_i = V[f_j], \qquad j \in R_i(N_l) \tag{4.4}$$

The meaning of eq. (4.4) is that rough region is expected to have many landmarks.

4.2 Alternatives

Path design $\mathcal{P}$ is given by a set of way points defined by the corresponding grid numbers. Each grid in $\mathcal{P}$ is described by a parameter p_i. The total number of way points, denoted by N and way points p_i are decision parameters. 630 path alternatives have been generated, each starting from the same point. Each alternative has different set of way points p_i, and different length of the path N. In each designed path the way point p_i are selected randomly from the neighborhood of the previous way point p_{i-1}. The neighborhood means 100th neighbor, where 1st neighbor means a grid selected randomly from three adjacent grids of the previous way point p_{i-1}. The path length N is set from 1 up to 20, in order to make the largest path to spread over the half surface of the asteroid. Fig. 8 charts some examples of alternatives of path design.

4.3 Criteria Values

Based on eq.(3.1) $\sim$ (3.6) using the parameters defined by eq.(4.1) $\sim$ (4.4), the values for each criteria are calculated. An example of values for each criteria along with alternatives are plotted in Fig. 9. Thresholds α_r and α_w in criteria 4th and 5th are both $1/2 (= \cos 30^\circ)$.

4.4 Analysis of Simulation Results

MCAA tool has found 109 Pareto efficient solutions out of the 630 generated alternatives and proposed the alternative no. 58 as an initial proposed solution, where all the preferences are set to be equal. When the user specifies large preference on obtainable information, MCAA proposed no. 352 as Fig. 10. The alternative no. 352 has the best value

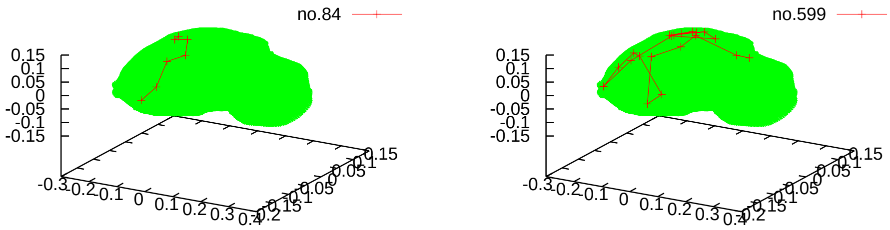

Fig. 8: Examples of path design : the left path no. 84 is shorter and not far from the start point while the right path no. 599 has large number of way points and has more commodious region to move.

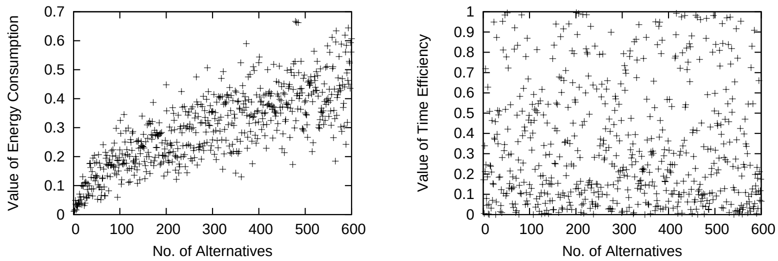

Fig. 9: Values of obtainable information : values of energy consumption increases according with the path-length while values of time efficiency has no relation with path-length.

in information criterion among the generated alternatives. When another preferences has been specified as large value on energy consumption, MCAA proposed the alternative no. 22 shown in Fig. 11. When the user wants to improve the value of criterion representing the device risk, MCAA proposed the alternative no. 1 as illustrated in Fig. 12. The alternative no. 22 has high value in energy consumption criterion, and the alternative no. 1 has the best value of the device risk criterion and also the energy consumption.

These examples show that MCAA succeeds to propose solutions that fit diverse user's preferences.

Analysis of the results presented in Fig. 10 through Fig. 12 shows that alternative no. 352 has a large value of obtainable information and a small value of time efficiency, while the alternative no. 22 and no. 1 have large (meaning good, because the criteria values have been normalized by the MCAA to a scale, in which 1 denotes the best value) values in energy consumption, device risk and time efficiency, and a small value in obtainable information. This is because alternatives no. 1 and no. 22 have relatively short paths, and alternative no. 352 has a much longer path (a shorter path implies less information value than a long one). Then we specified relatively large preferences in both obtainable information and device risk, and analyzed the results.

First, we specified large preferences for two criteria (obtainable information and device risk) and the solution was again alternative no. 352. Second, we got path no. 1 again when we specified the largest preference for the device risk and a large preference for obtainable information, and a smaller preference for position uncertainty.

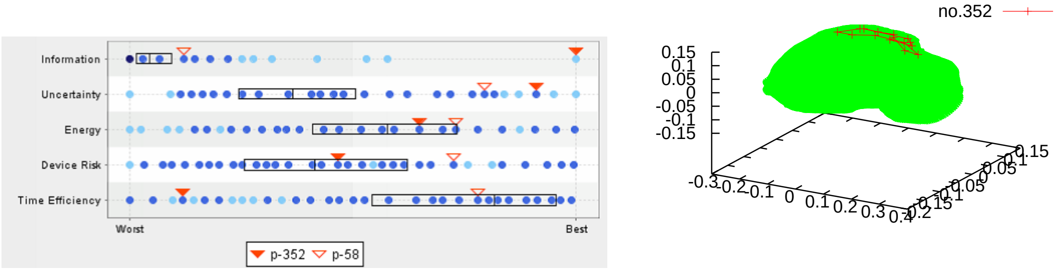

Fig. 10: An example of alternative analysis (left) and the designed path no. 352 (right) : when large preference is specified on obtainable information, the alternative no. 352 has been proposed.

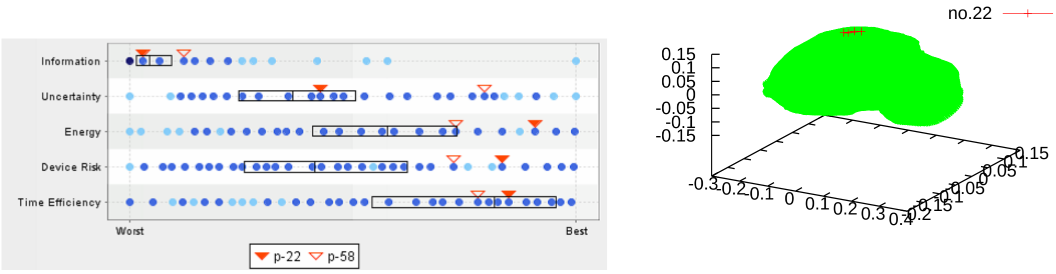

Fig. 11: An example of alternative analysis (left) and the designed path no. 22 (right) : when large preference is specified on energy consumption, the alternative no. 22 has been proposed.

Third, we used another MCAA method, for which the user can directly specify one of the following requirements for each criterion: ”improve”, ”stabilize”, ”free” and ”relax (worsen)”. We specified ”improve” for obtainable information value, ”stabilize” for the device risk, and ”relax” for time efficiency. As shown in Fig. 13 the corresponding Pareto alternative is path no. 5.

As Fig. 13 shows, the alternative no. 5 has a small value in obtainable information. Fig. 14 shows the top 6 alternatives (no. 352, 331, 443, 558, 500 and 159) in terms of obtainable information criterion, and the best alternative (no. 2) of value in respect of the risk criterion. From Fig. 14 one can conclude that no alternative has large values for both obtainable information and device risk criteria. The alternative no. 159 has relatively large value in device risk, and has 6th large value in information value. Thus, among the generated alternatives there is none that has large values of both information and device risk criteria.

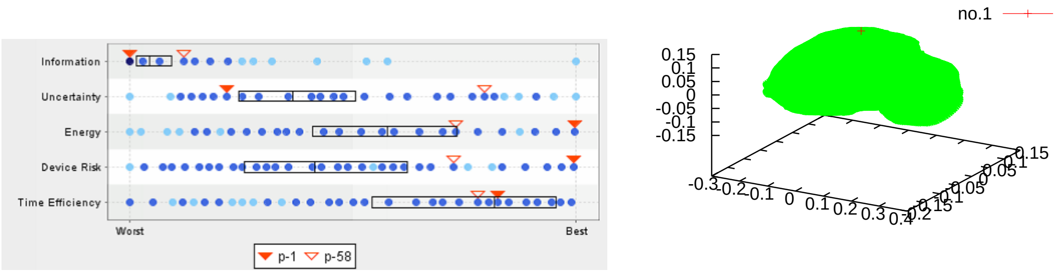

Fig. 12: An example of alternative analysis (left) and the designed path no. 1 (right): when large preference is specified on energy consumption, the alternative no. 1 has been proposed.

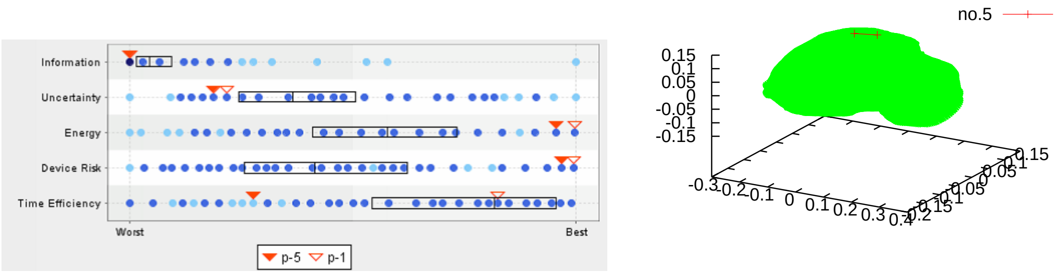

Fig. 13: An example of alternative analysis (left) and the designed path no. 5 (right) : when the user specifies large preference on both obtainable information and device risk.

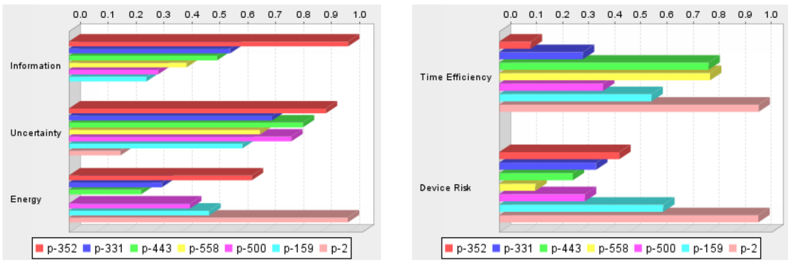

Fig. 14: Alternatives comparison in value of obtainable information and device risk

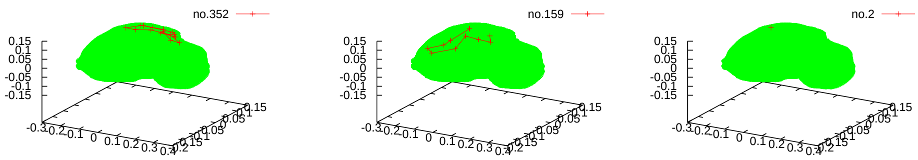

Fig. 15: Alternatives no. 352, no. 159 and no. 2 in Fig. 14.

5 Summary

The paper presents a man-machine control problem of a space robot, and a corresponding remote control model composed of three submodels: estimation of the area, path-design, and autonomous control. We focused on operator's decision making problem and defined operator's criteria numerically. The model has been verified by simulation using the shape data of asteroid Itokawa. The parameters need to be discussed more because they are defined based only on variance of facet direction. The path alternatives have been designed automatically on randomly generated directions; the path design shall be improved by considering the goal position together with the current information about the terrain.

In future research we will exploit the results reported in this paper, and focus on the design of the autonomous robot control, which will reflect the operator's preferences in implementation of the autonomous part of the robot control. After designing the robot's autonomous control, we will discuss what is needed for flexible and complementary control between an operator and a robot. Therefore the operation model described in this report is the first step in our research on the cooperative man-machine control.

References

[1] Kawaguchi, Fujiwara, Hashimoto, MUSESC(HAYABUSA): The mission and results, Proceedings of the IEICE General Conference, SS.22SS.27(2006), 2006

[2] Tetsuo Yoshimitsu, Takashi Kubota, Ichiro Nakatani, Tadashi Adachi, Hiroaki Saito, ”Micro-hopping robot for asteroid exploration”, Acta Astronautica 52, 441-446, 2003

[3] Sayaka Kanata, Hiroaki Nakanishi, Tetsuo Sawaragi, Tetsuuo Yoshimitsu, and Ichiro Nakatani, ”RadioWave Based Localization of a Rover for a Small Planetary Body”, The 27th IASTED International Conference on Modeling, Identification and Control, 596-036, 2008

[4] http://hayabusa.sci.isas.jaxa.jp/shape.pl

[5] Gaskell et al., Landmark Navigation Studies and Target Characterization in the Hayabusa Encounter with Itokawa, AIAA paper 2006_6660, AAS/AIAA Astrodynamics Specialists Conf., Keystone, CO, Aug., 2006

[6] Janusz Granat, Marek Makowski, ISAAP - Interactive Specification and Analysis of Aspiration -Based Preferences, European Journal of Operational Research, vol.122, no 2, 2000

[7] M. Makowski and J. Granat and H. Ren, MCAA: Multi-Criteria Analysis of Discrete Alternatives. Part II: User Guide and Tutorial, Interim Report, International Institute for Applied Systems Analysis, 2008 (in preparations; draft available on demand)