MOTION PLANNING IN ATTITUDE MANEUVER USING NON-HOLONOMIC TURNS FOR A TRANSFORMABLE SPACECRAFT

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ABSTRACT

As a new spacecraft system, a transformable spacecraft which can transform its shape according to purpose is conceivable. In this research, it is shown that attitude maneuver of a transformable spacecraft can be achieved by using non-holonomic motions which utilize the transformability of the spacecraft itself. In addition, a simple motion planning method for such a maneuver is studied.

可変構造宇宙機の非ホロノミック運動を用いた姿勢マヌーバにおける姿勢移行計画

要旨

新しい概念の宇宙機として、軌道上で目的に応じて形状を変化できる可変構造宇宙機がある。本研究では、可変構造宇宙機の姿勢マヌーバが、宇宙機の構造が可変であること自体を用いた、非ホロノミック運動により実現可能であることを示す。さらに、非ホロノミック運動を用いた姿勢マヌーバにおける、姿勢移行経路計画の方法について、貪欲アルゴリズムを用いた手法を検討する。

INTRODUCTION

As an innovative spacecraft system, a transformable spacecraft, which consists of multiple modules connected with each other by hinges or universal joints, is studied in the Japan Aerospace Exploration Agency (JAXA). They are equipped with motors that rotate the modules within a certain range of angle, which allows the spacecraft to configure various kinds of three-dimensional shapes. As for the modules, their shape is arbitrary and one of the simplest is panel shape, for example.

An example of application of a transformable spacecraft is a space telescope. Supposing a spacecraft consisting of a number of panels connected with each other by hinges, they can be folded to be compact as a whole at the time of launching, unfolded to configure a large plane and recomposed to configure multiple kinds of telescope on orbit, which are different in field of view and focal distance (Fig. 1).

One of the most innovative points of a transformable spacecraft is that it is capable of the non-holonomic rotation as a way of attitude maneuver by utilizing the transformable structure. This rotation makes it possible to change the attitude of the spacecraft largely without using fuel or external forces/torques.

A non-holonomic rotation is a way of rotation around an axis a torque cannot be input directly. This is achieved with a combination of internal forces/torques in the plane normal to the axis mentioned above. Although a non-holonomic rotation is not limited to a rotation caused by internal torques/forces, we define the one as the non-holonomic rotation here, which we call the “non-holonomic turn” hereafter.

In this paper, we first show that it is expected that any kinds of attitude can be achieved in principle using a simple model, although it may not be optimal. After that, an idea of better motion planning in the maneuver using greedy algorithm is proposed. The path of attitude transition using non-holonomic turns generally cannot be determined uniquely. Therefore, it is interesting to find the optimal path. However, we are not going into the optimality in this paper and leave it to our future work.

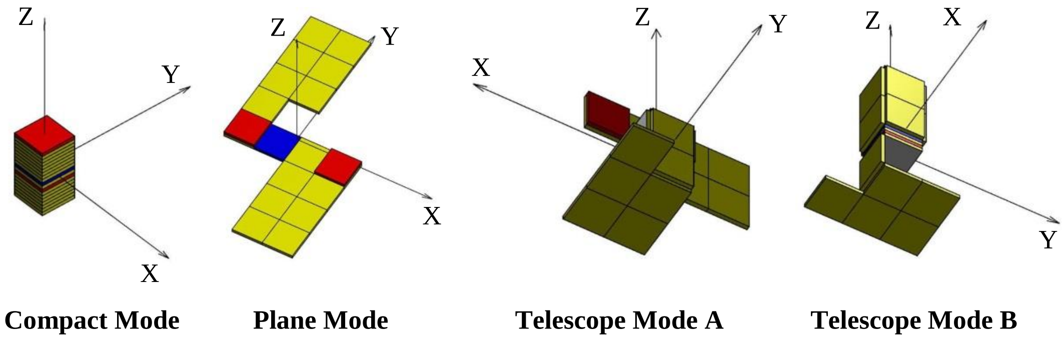

Figure 1. Shape change of a transformable spacecraft

NON-HOLONOMIC TURN

As an example to demonstrate a non-holonomic turn, we assume a simple model composed of three panels and two hinges as shown in figure 2. This spacecraft has only two degrees of freedom for rotating, which are around X and Y axes attached to the center plate. For simplicity, we assume that only one hinge is rotated at one time in the range from -90 to 90 degrees. When hinge A is rotated by α degrees first and hinge B is rotated by β degrees next, all the panel modules rotate with respect to the inertial frame so that it satisfies the law of conservation of angular momentum. Then in case A is rotated by $-\alpha$ degrees first and hinge B is rotated by $-\beta$ degrees next, although the shape of the spacecraft returns to its initial state, the attitude is changed even though no external forces/torques are applied as shown in figure 3. This is because the inertia tensor is different between at the time of initial bending and going back. This is an example of a non-holonomic turn and we consider this sequence as one non-holonomic turn afterward. An important point to make is that the final attitude of the spacecraft depends on the order of hinges that we rotate and their angle values.

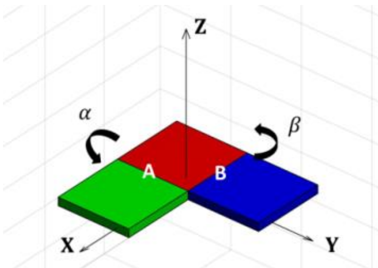

Figure 2. A simple model of a transformable spacecraft

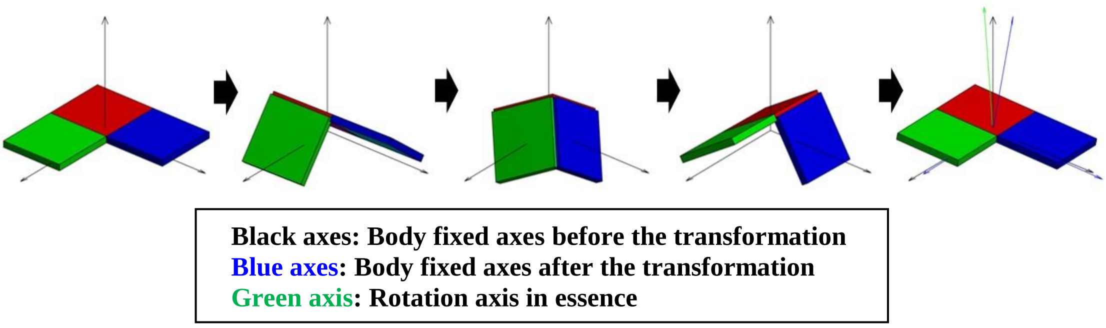

Figure 3. Attitude change after a non-holonomic turn

As shown in the figure 3 with a green axis, a non-holonomic turn can be regarded as a rotation around a certain axis. Figure 4 shows such direction vectors $\boldsymbol{d_r}$ of non-holonomic turns calculated numerically and plotted on a unit sphere. The hinge angles are varied from -90 to 90 degrees with a step of 5 degrees. The calculation is conducted assuming each plate is 0.1 m high, 1 m wide, 1 m long and 10 kg weight. The color expresses the efficiency ε of rotation defined by the following equation.

$$\varepsilon = \frac{\theta_r}{2(|\alpha| + |\beta|)} \tag{1}$$

Here θ_r is the rotation angle around $\boldsymbol{d_r}$ and it is uniquely determined according to each $\boldsymbol{d_r}$. It is obvious that the dots don't cover the whole surface of the sphere. Large white areas show directions the spacecraft cannot rotate around by single non-holonomic turn.

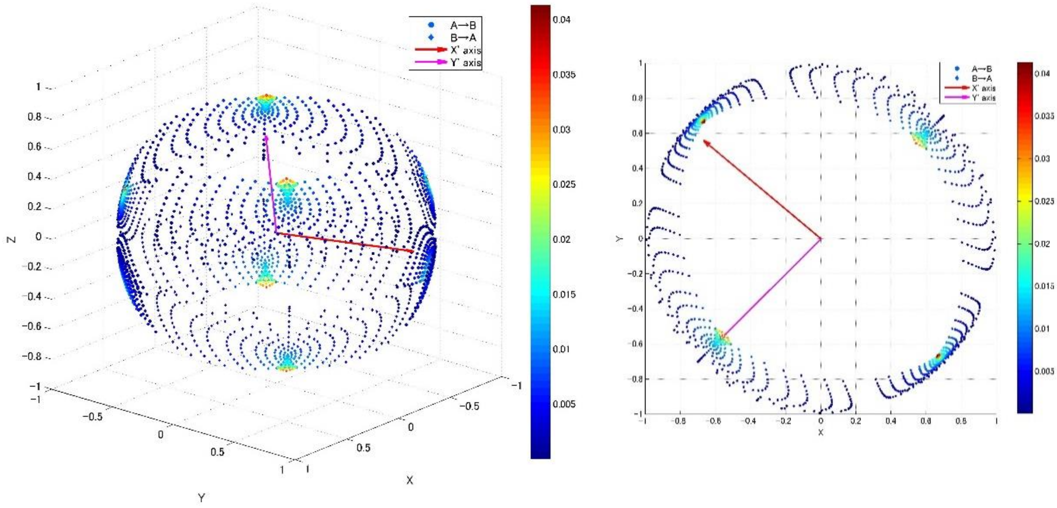

Figure 4. Direction vectors of non-holonomic turns

ATTITUDE MANEUVER USING NON-HOLONOMIC TURNS

Attitude maneuver is conducted by the repetition of non-holonomic turns with different patterns and angles.

Attitude Maneuver Using Two Orthogonal Axes

Here we first discuss the possibility of any kinds of intended attitude maneuver. Let us choose two orthogonal axes X' and Y' from rotation direction vectors mentioned in the previous section and define their right-handed orthogonal axis as Z'. Then, it is possible to rotate around Z' axis by the repetition of rotations around X' and Y' axes, which allows the spacecraft to achieve almost any kinds of attitude. However, the rotation angle by a non-holonomic turn is fixed depending on the axis we choose, and therefore attainable rotation angles around X' and Y' are discrete, causing some errors to the final attitude. The smaller the rotation angles of two orthogonal axes we choose, the smaller the remaining errors become. On the other hand, the number of non-holonomic turns becomes larger and efficiency of the maneuver gets worse, the path being far from optimal.

Figure 5 (right) shows a simulation result of attitude maneuver using two orthogonal axes. Remaining errors and the number of non-holonomic turns required are on the table 1, and other simulation conditions are on the table 2. Two orthogonal axes chosen are shown in the figure 4 and 5 (left) graphically. Hereafter, the efficiency of an attitude maneuver is evaluated using the value of total rotation angles of both hinges required for the maneuver.

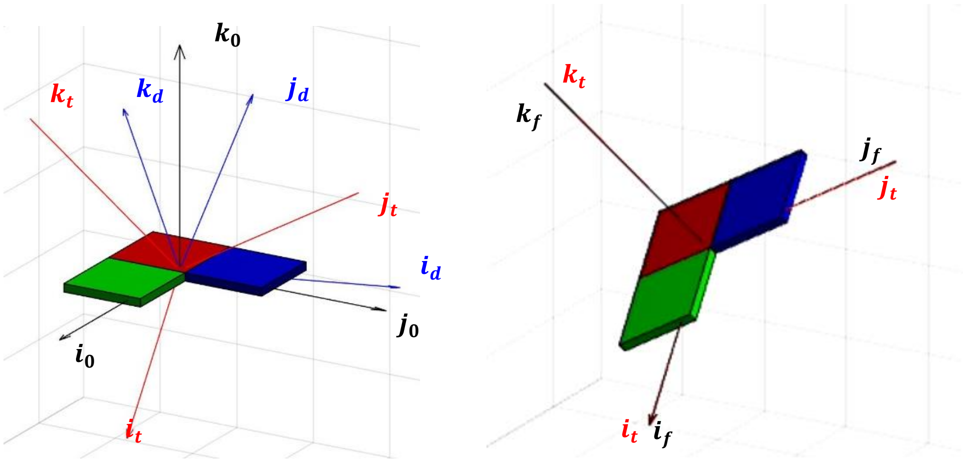

Figure 5. Simulation result (Two Orthogonal Axes)

Table 1. Simulation result (Two Orthogonal Axes)

Error of X axis	0.21 [deg]
Error of Y axis	0.24 [deg]
Error of Z axis	0.13 [deg]
Number of non-holonomic turns	169
Cost (Total rotation angles of hinges)	29,940 [deg]

Table 2. Simulation conditions (Two Orthogonal Axes)

Target attitude (1-2-3[φ-θ- ψ] Euler angle system)	$\varphi = 30, \theta = 30, \psi = 0$ [deg]
Direction of X' axis, $\boldsymbol{i_d}$	$(-0.751136, 0.629920, -0.197471)^T$
Pattern of the non-holonomic turn	A -50 → B -30 → A 50 → B 30 [deg]
Rotation angle around X' axis	1.06 [deg]
Direction of Y' axis, $\boldsymbol{j_d}$	$(-0.649284, -0.649284, 0.396057)^T$
Pattern of the non-holonomic turn	A 45 → B -45 → A -45 → B 45 [deg]
Rotation angle around Y' axis	1.01 [deg]

Motion Planning Using Greedy Algorithm (Unidirectional Search)

The method of attitude maneuver discussed in the previous subsection is naïve and seems inefficient. Therefore, finding better paths is the next problem. In this subsection, motion planning method using greedy algorithm is proposed.

We consider motion planning from the initial attitude $\boldsymbol{q_i}$ to the target attitude $\boldsymbol{q_t}$. First we prepare a library of motion primitives which are direction cosine matrices (DCMs) produced from different patterns of single non-holonomic turn. In this paper, they are calculated numerically by changing hinge angles from -

90 to 90 degrees with a step of 5 degrees with two orders (A → B and B → A). Our motion planning problem here is to find the set of motion primitives $C_1, C_2, \cdots, C_n$ that satisfies the following equation from the library.

$$C_t = C_n C_{n-1} \cdots C_1 C_i \tag{2}$$

Here C_t and C_i are the DCMs of the target and the initial attitude respectively. In greedy algorithm, the primitive that makes the metric between the consequent attitude $\boldsymbol{q}$ and the target attitude $\boldsymbol{q_t}$ smallest is chosen in each step. In this paper, we define the metric ρ as follows although there are many other options.

$$\rho = (1 - \boldsymbol{q} \cdot \boldsymbol{q_t})^2 \tag{3}$$

The simulation result using the same condition as the one in the previous subsection is shown in figure 6 and table 3. The algorithm is terminated when the error of each axis of body fixed coordinate becomes within 1 degree. As shown in the table 3, the cost is much smaller than the naïve method.

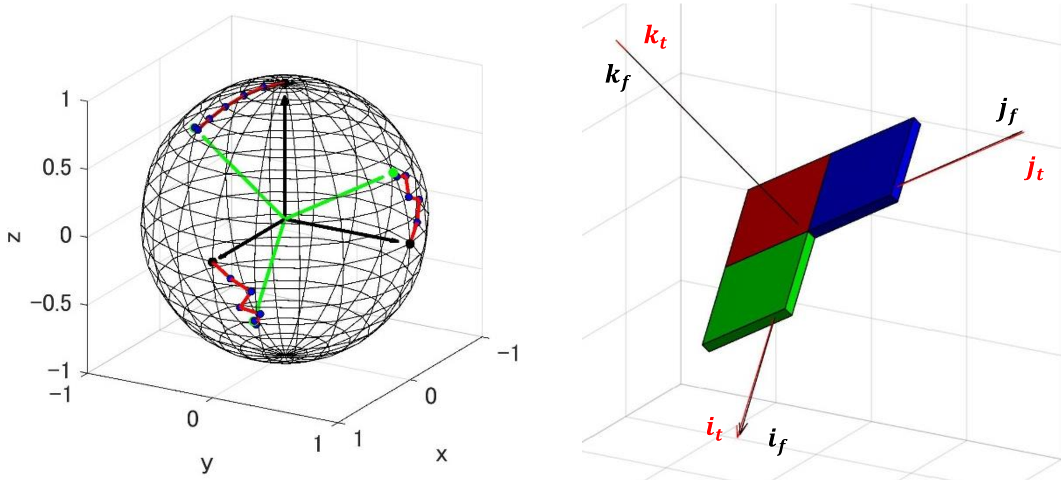

Figure 6. Simulation result (Unidirectional Greedy Algorithm)

Table 3. Simulation result (Unidirectional Greedy Algorithm)

Error of X axis	0.54 [deg]
Error of Y axis	0.54 [deg]
Error of Z axis	0.02 [deg]
Number of non-holonomic turns	6
Cost (Total rotation angles of hinges)	1,980 [deg]

Motion Planning Using Greedy Algorithm (Bidirectional Search)

In the path finding problem, bidirectional methods often show higher performance than unidirectional ones. In this subsection, another simulation using greedy algorithm in which the path is bidirectionally searched is conducted for comparison.

In the bidirectional search, our motion planning problem is to find the set of motion primitives $C_{f1}, C_{f2}, \cdots, C_{fm}, C_{b1}, C_{b2}, \cdots, C_{bn}$ that satisfies the following equation from the library.

$$C_{bn}^{-1} C_{bn-1}^{-1} \cdots C_{b1}^{-1} C_t = C_{fm} C_{fm-1} \cdots C_{f1} C_i \tag{4}$$

New attitudes $\boldsymbol{q_f}$ and $\boldsymbol{q_b}$ are obtained alternately starting from the initial and the target attitudes respectively until they coincide. The motion primitive that makes the following metric ρ the smallest is chosen in each step.

$$\rho = \left(1 - \boldsymbol{q_f} \cdot \boldsymbol{q_b}\right)^2 \tag{5}$$

Figure 7 and table 4 show the simulation result of motion planning using bidirectional greedy algorithm. Although the cost is the same as the one of unidirectional search for this case, there found other cases that bidirectional greedy algorithm was easier to converge.

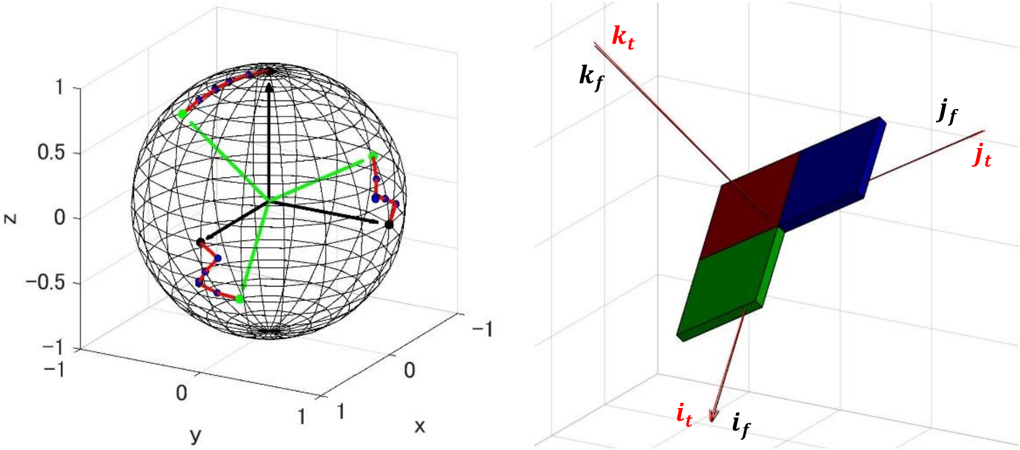

Figure 7. Simulation result (Bidirectional Greedy Algorithm)

Table 4. Simulation result (Bidirectional Greedy Algorithm)

Error of X axis	0.43 [deg]
Error of Y axis	0.14 [deg]
Error of Z axis	0.45 [deg]
Number of non-holonomic turns	6
Cost (Total rotation angles of hinges)	1,980 [deg]

CONCLUSION

Motion planning methods in attitude maneuver using non-holonomic turns for a transformable spacecraft was studied and some simulations were conducted. It was shown that the greedy algorithm seemed to be able to produce good solutions, which however cannot to be regarded as optimal. In the future research, we will pursue the method to obtain the shortest path and try to apply to the real model which is much more complex. We will also study on the method to change configurations and attitude simultaneously.

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