

# HIGH FIDELITY DIRECT TRANSCRIPTION METHOD FOR OPTIMIZATION OF MANY REVOLUTION, LOW-THRUST TRAJECTORIES

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We investigate new ideas of direct transcription method for modeling low-thrust trajectories as an improvement to the Sims-Flanagan model. First, the sequential impulsive  $\Delta V$  transcription is replaced by integrated continuous thrust arcs to improve the fidelity of the dynamical model. Next, to enable the simulation of trajectories with multiple revolutions, we adopt a transformation in the independent variable from time to true anomaly. The obtained new algorithm is able to produce an operational trajectory accounting for the real spacecraft dynamics and adapting the segment duration on-line improving the final trajectory optimality.

## INTRODUCTION

A direct optimization method proposed by Sims and Flanagan<sup>1</sup> suggests that low-thrust trajectories can be modeled as a series of impulsive  $\Delta V$  connected by conic arcs. The method is fast and robust and has been applied in previous works for preliminary mission design.<sup>2,3</sup> However with its impulsive  $\Delta V$  transcription, the Sims-Flanagan method can fail to accurately represent the actual dynamical model unless the number of impulses is increased and thus at the cost of slowing down the overall optimization.

In this paper, we study new transcription methods to improve the accuracy of the Sims and Flanagan model without increasing the dimension of the problem. The works extends some of the ideas presented at the fifth international meeting on celestial mechanics CELMEC V<sup>4</sup> and the International Conference on Astrodynamics Tools and Techniques (ICATT).<sup>5</sup> The first improvement is to replace the impulses with continuous thrust, where low-thrust arcs are numerically propagated. The magnitude and direction of the thrust are part of the optimization variables and are assumed to be constant throughout a segment. Perturbations can be included, in the propagation, to further improve the fidelity of the model. The modification introduces a performance penalty due to the higher computational costs of the integration with respect to a simple Keplerian propagation between impulses. In order to tackle this issue we introduce the use of Taylor integration<sup>6</sup> methods in place of the commonly employed Runge-Kutta-Fehlberg scheme, reducing the performance loss by almost one order of magnitude.

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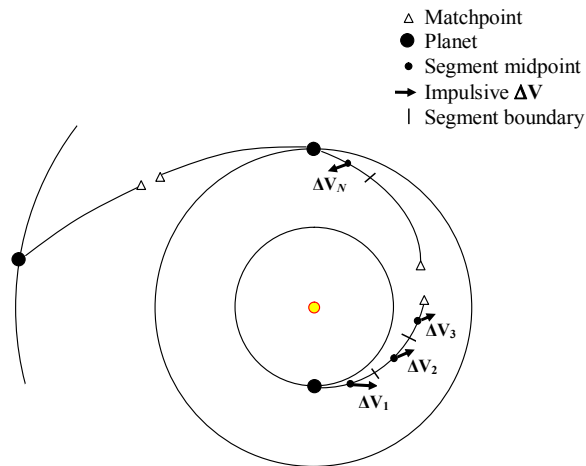
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A second improvement we introduce is to allow the time mesh to be optimized together with the trajectory. While this is a long unsolved issue in direct method for trajectory optimization, we manage to obtain an efficient algorithm by introducing a transformation in the true anomaly, in which the independent variable is changed from time to the true anomaly  $\theta$ , where the time variation of  $\theta$  is related with a differential equation. By doing so, and adding only one constraint to the optimization problem, segments are automatically distributed more densely near the central body (where speed is usually higher) along the optimal solution and thus on-line mesh adaptation is obtained at the cost of an acceptable performance loss.

As compared with previous work,<sup>5</sup> which adopt the the Sundman transformation,<sup>7</sup> we find that the orbital parameter  $\theta$  has a more obvious physical meaning than the Sundman parameter  $s$ . It is also more convenient to specify the location of the thrust using an angle relative to the orbital frame. Thus we choose the true anomaly  $\theta$  as the new transcription parameter in our new model.

We present a numerical example to compare results between the original and the new methods. The resulting tool has the further advantage of being suitable for different phases of the mission design, from preliminary, where global optimization methods need a rather simple and low-dimensional transcription, to operational where dynamics need to be accounted for in a precise manner and optimality is sought.



**Figure 1:** Impulsive  $\Delta V$  transcription of a low-thrust trajectory, after Sims and Flanagan<sup>1</sup>

## THE ORIGINAL SIMS-FLANAGAN MODEL

In 1999, Sims and Flanagan proposed a direct method for optimising low-thrust trajectories, where later the software packages GALLOP<sup>8</sup> and MALTO<sup>9</sup> are developed based on this model. Figure 1 briefly illustrates such a trajectory model. The whole trajectory is divided into legs which begin and end with a planet. Low-thrust arcs on each leg are modeled as sequences of impulsive maneuvers  $\Delta V$ , connected by conic arcs. We denote the number of impulses (which is the same as the number of segments) with  $N$ . The  $\Delta V$  at each segment of equal duration should not exceed a maximum magnitude,  $\Delta V_{max}$ , where  $\Delta V_{max}$  is the velocity change accumulated by the spacecraft when it is operated at full thrust during that segment:

$$\Delta V_{max} = (F_{max}/m)(T_f - T_0)/N \quad (1)$$

where  $F_{max}$  is the maximum thrust of the low-thrust engine,  $m$  is the mass of the spacecraft,  $T_0$  and  $T_f$  is the initial and final time of a leg. The spacecraft mass is propagated using the rocket equation:<sup>10</sup>

$$m_{i+1} = m_i \exp(-\Delta V_i / g_0 I_{sp}) \quad (2)$$

where the subscript  $i$  denotes the mass and  $\Delta V$  on the  $i$ -th segment,  $g_0$  is the standard gravity (9.80665 m/s<sup>2</sup>), and  $I_{sp}$  is the specific impulse of the low-thrust engine.

At each leg, trajectory is propagated (with a two-body model) forward and backward to a match-point (usually halfway through a leg), where the spacecraft state vector becomes

$$\mathbf{S}_{mf} = \{r_x, r_y, r_z, v_x, v_y, v_z, m\}_{mf} \quad (3)$$

(and similarly for  $\mathbf{S}_{mb}$ ), where  $r$  and  $v$  are respectively the position and velocity of the spacecraft and the subscripts represents the Cartesian  $x$ ,  $y$ ,  $z$  components. The forward- and backward-propagated half-legs should meet at the matchpoint, or the mismatch in position, velocity, and mass:

$$\mathbf{S}_{mf} - \mathbf{S}_{mb} = \{\Delta r_x, \Delta r_y, \Delta r_z, \Delta v_x, \Delta v_y, \Delta v_z, \Delta m\} \quad (4)$$

should be less than a tolerance in order to have a feasible trajectory.

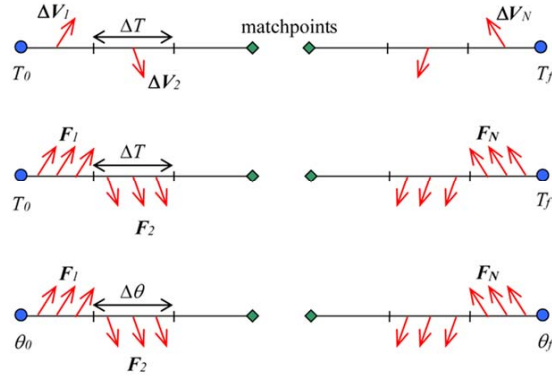
The problem is transcribed into a nonlinear programming problem (NLP), where the objective is to maximize the final spacecraft mass subjected to the constraints on the maximum  $\Delta V$  and the state mismatch, while the decision variables of the problem are listed below:

- the departure epoch  $T_0$
- the departure velocity relative to the earth  $V_\infty$
- for each leg and each segment, the magnitude of the impulse and direction
- for each swingby, the incoming and outgoing velocities relative to the planet
- for each swingby  $j$ , the swingby epoch  $T_j$
- the arrival epoch  $T_f$

For a rendezvous mission, the arrival velocity to the destination is not included in the set of variables, as it is, by construction of the model, zero relative to the planet. To solve the NLP, we use a software package called SNOPT<sup>11,12</sup> which implements sequential quadratic programming (SQP).

## IMPROVEMENT TO TRAJECTORY MODEL

From the beginning, the use of the Sims-Flanagan model is limited to preliminary mission design, in which the results are not expected to be accurate up to the operation level. In terms of the fidelity of the model, there are two areas in the Sims-Flanagan model that can lead to loss in accuracy: (1) the use of impulses; and (2) the insufficient number of segments. To address these issues, we introduce two improvements:



**Figure 2:** Schematics of the three trajectory models. Top: Impulsive  $\Delta V$ ; Middle: Continuous thrust in the time-space; Bottom: Continuous thrust in the  $\theta$ -space

- Impulsive  $\Delta V$  are replaced by continuous thrust to improve the fidelity of the trajectory dynamics. In order to keep a reasonably low computing time, we employ a Taylor integration scheme showing an order of magnitude performance gain with respect to the classical Runge-Kutta methods.
- An adaptive time mesh is obtained on the segments via the  $\theta$  transformation to improve on the optimality of the final trajectory.

### The Taylor Integration Method

When replacing the original impulsive  $\Delta V$  transcription with a continuous fixed thrust transcription, the optimization process becomes slower as the optimization relies on a numerical integration scheme of a higher complexity with respect to a simpler ballistic arc solver. Efficiency is essential to keep the CPU time penalty at a minimum level. For this purpose, we report the comparison, in terms of CPU time and accuracy, among classical Runge-Kutta-Fehlberg methods and the Taylor integration.<sup>6</sup> The tests have been done having in mind the typical algorithm call done during an optimization procedure that uses our approach. An improvement of one order of magnitude in CPU time (while keeping the integration accuracy to the same level) is found.

**Comparison set-up** We consider the set of differential equations describing the motion of a spacecraft subject to a fixed thrust force in the interplanetary medium. This ‘fixed thrust problem’ is at the basis of the ideas on direct transcription methods presented by some of these authors during the fifth international meeting on celestial mechanics CELMEC V<sup>(4)</sup> and that motivated the current paper. Since in the proposed new direct transcription method the fixed thrust problem needs to be solved a large amount of times (in each segment) and with diverse initial conditions and thrust vectors we focus the algorithmic comparison to those cases representative of such a process. The equations, in a non dimensional form, are the following:

$$\begin{aligned}
r &= \sqrt{x_1^2 + x_2^2 + x_3^2} \\
\dot{x}_1 &= x_4 \\
\dot{x}_2 &= x_5 \\
\dot{x}_3 &= x_6 \\
\dot{x}_4 &= -x_1/r^3 + u_1 \\
\dot{x}_5 &= -x_2/r^3 + u_2 \\
\dot{x}_6 &= -x_3/r^3 + u_3
\end{aligned} \tag{5}$$

The mass is not considered for the purpose of this comparison, but will be included in the trajectory model described later. To test the integration schemes,  $N = 10000$  different Cauchy problems have been generated at random considering  $x_i(0), u_i$  uniformly distributed in  $x_i(0) \in [0.1, 2]$  and  $u_i \in [0.0001, 0.01]$ . The final integration time has been also set to be random and  $t_f \in [\pi/20, 10\pi]$ . The same problems were solved using a Runge-Kutta-Fehlberg integration scheme (in the implementation of the GAL libraries<sup>13</sup>) and a Taylor integration scheme (implemented using the tool ‘‘taylor’’<sup>14</sup>). In order to test the speed and the precision of the solvers, we propagate each problem from  $x_i(0)$  for  $t_f$ , we then take the result and propagate backwards for  $t_f$  reaching the point  $x_i^f$ . By doing this, as we know the exact result of the propagation that is  $x_i(0)$ , we evaluate the precision of the propagation defining the propagation error as  $err = \sum_{i=1}^6 (x_i(0) - x_i^f)^2$ . Each algorithm is tested on the same set of randomly generated Cauchy problems. In all cases, no minimum step size is used and the same parameter  $\epsilon$  is passed to the RKF integrators as the absolute error, and to the Taylor integrator as both absolute and relative error. The initial trial stepsize of 0.1 is set to the RKF integrators.

**Results** From the results outlined in Table 1 it is clear that the Taylor integrator is outperforming the RKF both in speed and accuracy confirming in the low-thrust fixed direction problem the same performance gain levels already reported in past literature.<sup>6,15</sup> From the table we may also, empirically, establish that  $\epsilon = 10^{-10}$  is a good compromise between speed and accuracy and can thus be used as a default parameter to call the Taylor integrator. The speed gained by employing the Taylor integrator is roughly one order of magnitude.

**Table 1:** Algorithm Performance. Speed is measured in seconds and refers to all the  $N$  integrations (forward+backward). Max. Err. is the maximum integration error made in the  $N$  propagation. Note that this is a real error, not an estimation as explained above.

$\epsilon$	RKF 5(6)		RKF 7(8)		Taylor	
	Speed (s)	Max. Err.	Speed (s)	Max. Err.	Speed (s)	Max. Err.
1.00e-04	0.807	3.12e+01	1.13	7.51e-01	0.659	9.71e-04
1.00e-08	2.61	1.39e-03	2.37	1.18e-03	1.36	4.75e-11
1.00e-10	5.61	1.48e-05	3.94	1.32e-05	1.98	6.39e-15
1.00e-14	32.5	1.96e-09	10.9	6.11e-10	2.91	3.59e-20

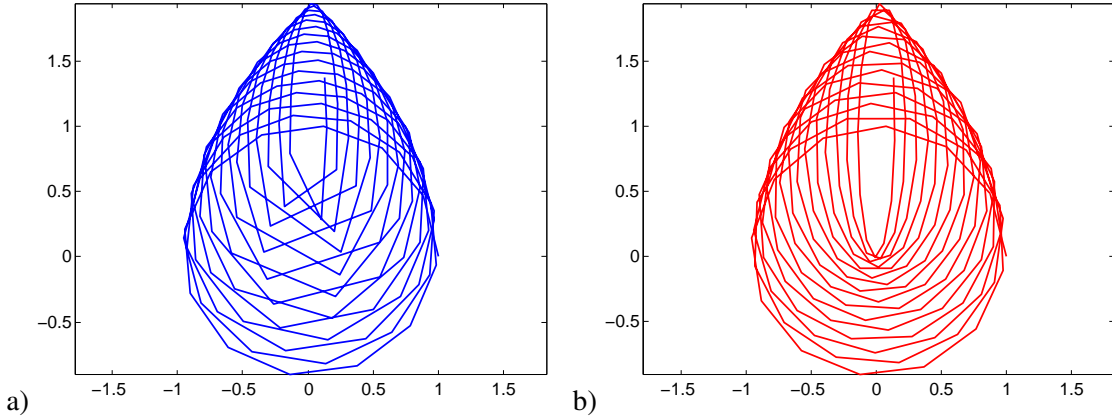
## The $\theta$ Transformation

Following the idea of the Sundman<sup>7</sup> transformation, we introduce a transformation of independent variable in the equations of motions, from time to true anomaly  $\theta$ . The following provides the rate of change of true anomaly:

$$\frac{d\theta}{dt} = \frac{h}{r^2} + \frac{1}{eh} [(p)\cos(\theta)u_r - (p+r)\sin(\theta)u_L] \quad (6)$$

where  $h$  is the angular momentum,  $r$  is the distance to the central body,  $e$  is the eccentricity,  $p$  is the semi-latus rectum,  $u_r$  is the acceleration in the radial direction, and  $u_L$  is the acceleration 90 degrees from the position vector in the velocity-increasing direction. Consider Eq.(5) and use the transformation from Eq. Eq.(6), we obtain the following set of equations:

$$\begin{aligned} r &= \sqrt{x_1^2 + x_2^2 + x_3^2} \\ \frac{dx_1}{d\theta} &= x_4 / \frac{d\theta}{dt} \\ \frac{dx_2}{d\theta} &= x_5 / \frac{d\theta}{dt} \\ \frac{dx_3}{d\theta} &= x_6 / \frac{d\theta}{dt} \\ \frac{dx_4}{d\theta} &= (-x_1/r^2 + u_1) / \frac{d\theta}{dt} \\ \frac{dx_5}{d\theta} &= (-x_2/r^2 + u_2) / \frac{d\theta}{dt} \\ \frac{dx_6}{d\theta} &= (-x_3/r^2 + u_3) / \frac{d\theta}{dt} \\ \frac{dt}{d\theta} &= 1 / \frac{d\theta}{dt} \end{aligned} \quad (7)$$



**Figure 3:** A trajectory sampled with the same number of equally a) time spaced segments b)  $\theta$ -spaced segments

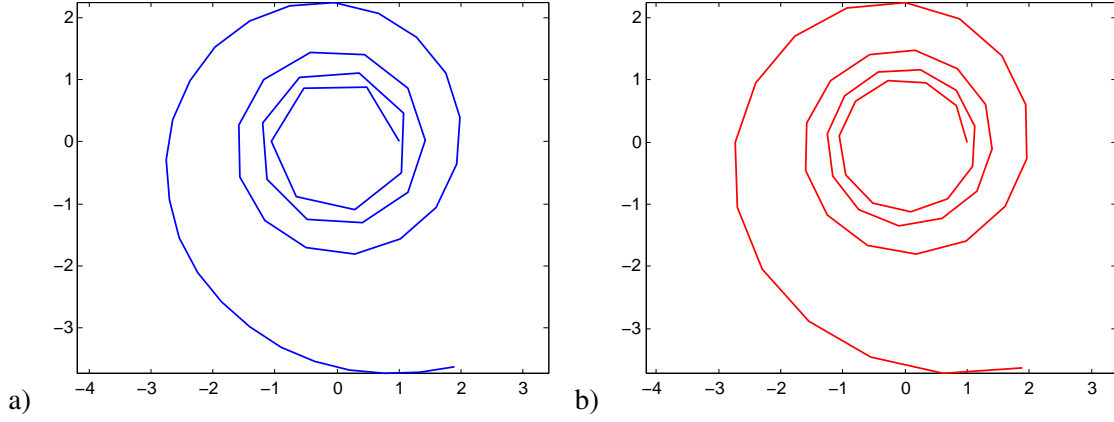
To demonstrate the effect of such a transformation on a numerical mesh, we take a circular orbit of radius one and propagate it forward with a constant thrust aligned along the  $x$  axis. In Figure 3a we visualize the obtained orbit using a uniform sampling in time, while in Figure 4b the same trajectory is visualized using the same number of samples, but equally spaced in the Sundman variable domain. The same is done in Figures 4a-b for a constant tangential thrust. These pictures clearly show the problem with using points equally spaced in time to define a mesh for a numerical algorithm: due to the conservation of energy the closer we get to the singularity the more potential energy we lose and thus acquire in terms in kinetic energy. This pumps up the body velocity substantially creating

**Table 2:** Parameters for an Earth-Mercury Rendezvous Mission.

Parameters	Values
Initial mass of the spacecraft	660.0 kg
Maximum thrust	92.3 mN
Specific impulse	3,337 s
Launch date	Apr. 9, 2007
Arrival date	Aug. 22, 2013
Launch $V_\infty$	$\leq 2.0$ km/s
Time of flight	6.37 years

**Table 3:** Optimal Final Mass for the Earth-Mercury Mission.

Method	No. of Variables	Optimal Final Mass, kg
Impulsive	97	392.9
Continuous $t$ -space	97	382.4
Continuous $s$ -space	98	387.0



**Figure 4:** A trajectory sampled with the same number of equally a) time spaced segments b)  $\theta$ -spaced segments

an unequal distribution of segments length bound to create numerical difficulties. The use of the  $s$  variable is one of the possible transformations able to alleviate such a problem.

## NEW TRAJECTORY MODELS

The implementation of the ideas reported above leads to new trajectory models that, when optimized, result in significant improvements on the optimality and feasibility over the original Sims-Flanagan method.

### Continuous thrust time-space propagation

In this model the impulses at each segment are replaced with continuous thrusts  $(F_x, F_y, F_z)$  which are assumed to be constant within the segment (see the middle scheme in Figure 2). Each leg of the trajectory is propagated forward and backward with equal-duration segments as before. The propagation of the trajectory changes from pure Keplerian to integration of the ordinary differential equations:

$$\begin{aligned}
 r &= \sqrt{r_x^2 + r_y^2 + r_z^2} \\
 F &= \sqrt{F_x^2 + F_y^2 + F_z^2} \\
 \dot{r}_x &= v_x \\
 \dot{r}_y &= v_y \\
 \dot{r}_z &= v_z \\
 \dot{v}_x &= -\mu r_x / r^3 + F_x / m \\
 \dot{v}_y &= -\mu r_y / r^3 + F_y / m \\
 \dot{v}_z &= -\mu r_z / r^3 + F_z / m \\
 \dot{m} &= -F / (g_0 I_{sp})
 \end{aligned}$$

### Continuous thrust $s$ -space propagation

For the *continuous thrust  $s$ -space* method, we apply the Sundman transformation<sup>7</sup> to change the independent variable from time  $t$  to  $s$ , and the differential equations in  $s$ -space becomes:



$$\begin{aligned}
r &= \sqrt{r_x^2 + r_y^2 + r_z^2} \\
F &= \sqrt{F_x^2 + F_y^2 + F_z^2} \\
\dot{r}_x &= rv_x \\
\dot{r}_y &= rv_y \\
\dot{r}_z &= rv_z \\
\dot{v}_x &= -\mu r_x / r^2 + r F_x / m \\
\dot{v}_y &= -\mu r_y / r^2 + r F_y / m \\
\dot{v}_z &= -\mu r_z / r^2 + r F_z / m \\
\dot{m} &= -r F / (g_0 I_{sp}) \\
\dot{t} &= r
\end{aligned}$$

where the derivatives are here meant to be taken with respect to the independent variable  $s$ . Here each leg of the trajectory is propagated forward from  $s_0$  and backward from  $s_f$  in equal  $s$ -space ( $\Delta s$ ). The time between the mesh is no longer constant and it is proportional to the radial distance  $r$ , which implies a shorter time mesh (a finer grid size or segment) is used when the spacecraft is closer to the central body. The 8th differential equation gives the condition for matching the time difference between the two endpoints:

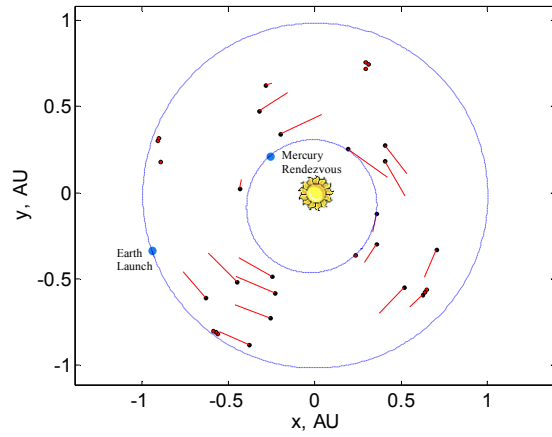
$$T_f - T_0 = \int_{s_0}^{s_f} r ds \quad (8)$$

To implement the  $s$ -space method for optimization, we assume  $s_0$  to be zero and solve for  $s_f$  to satisfy Eq. 8, which means an additional variable and constraint are added for each leg.

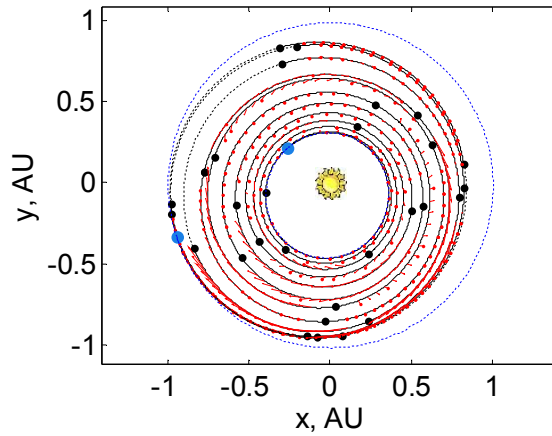
## NUMERICAL EXAMPLE

We demonstrate our new methods with a sample low-thrust mission to Mercury. Table 2 summarizes the mission specification for a spacecraft similar to the Deep Space 1 mission.<sup>16</sup> Instead of using a model of the SEP (solar electric propulsion) system, we simplify the problem a bit here by assuming a constant thrust and constant specific impulse engine. The launch and arrival dates are kept frozen for the test.

Figure 5a shows the trajectory found by the impulsive model, where the black dots denote the midpoint of the segments and the red lines represent the impulses. It is visually clear that for this fast rotating trajectory, the impulsive propagation method might not be able to have a fair representation of the actual low-thrust trajectory. With the same number of segments (30), the *continuous thrust time-space model* is able to fill up the "gap" between the impulses with low-thrust arcs (shown as red curves in figure 5b). Even with a lower final mass (see Table 3), the trajectory found by the continuous thrust method satisfies the real dynamical model which can be used as a trajectory for the actual mission (after adding other perturbative forces). The trajectory modeling can be further improved by converting to the  $s$ -space propagation method in figure 6a. In the  $s$ -space method, we note that when the spacecraft is near Mercury, the grid size is smaller than it is near Earth's orbit, while in the *time-space* method the segment duration is constant (see figure 6b). In this example, the implementation of the  $s$ -space propagation can automatically adapt the grid size (segment duration) to fit the radial distance (and hence the speed of the spacecraft) of the trajectory during the optimization. A smarter choice of the segment duration along the trajectory allows the



(a) Trajectory plot of an Earth-Mercury rendezvous mission optimized using impulsive  $\Delta V$  transcription (number of segments = 30).



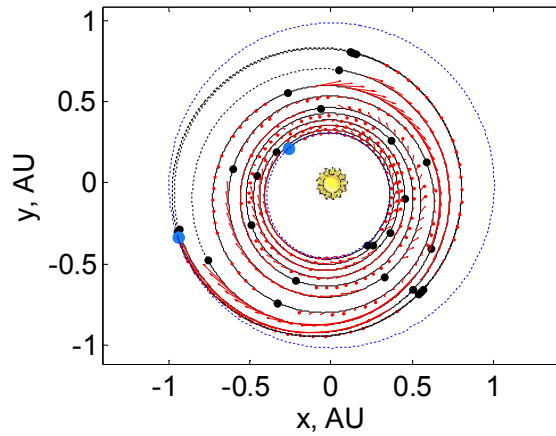
(b) Earth-Mercury trajectory found by continuous thrust time-space propagation.

**Figure 5:** Impulsive and continuous thrust optimal trajectories with equally spaced segments in time.

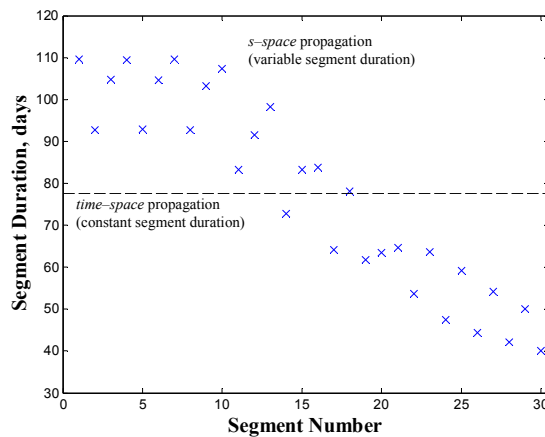
spacecraft to update its control (i.e. thrust) and therefore be more efficient, which explains why the final mass of the *s-space* is higher than the *time-space* method.

## CONCLUSIONS AND FUTURE WORK

We have successfully extended the Sims-Flanagan model to include the full dynamics of low-thrust trajectory. The change of independent variable via transformation with true anomaly can further improve the results through online adaptive time-mesh during the optimization. In the future, we hope to investigate a more general form of the angular transformation without singularity (e.g. true longitude)<sup>17</sup> and to perform some benchmarking of the new methods to compare their convergence speed and the accuracy.



(a) Earth-Mercury trajectory found by continuous thrust  $s$ -space propagation.



(b) Duration of each segment for the trajectory found by  $s$ -space propagation. The on-line mesh adaptation distributes the segment time duration in a convenient way using the Sundman transformation

**Figure 6:** Trajectory found using the Sundman transformation.

## ACKNOWLEDGMENT

The first author of this paper is supported by the Japan Society for the Promotion of Science, under the Short-term JSPS Postdoctoral Fellowship Program.

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