Interplanetary Trajectory Optimization with Swing-bys Using Evolutionary Multi-Objective Optimization

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Abstract. Interplanetary trajectory optimization studies mostly considered a single objective of minimizing travel time between two planets or launch velocity of spacecraft at the departure planet or maximizing delivered payload at the destination planet. Despite a few studies, in this paper, we have considered a simultaneous minimization study of both launch velocity and time of travel between two specified planets with and without the use of gravitational advantage (swing-by) of some intermediate planets. Using careful consideration of a Lambert's approach with the Newton-Raphson based root finding procedure of developing a trajectory dictated by a set of variables (departure date, swing-by planets, etc.), a number of derived parameters, such as time of flight between arrival and destination planet, date of arrival, and launch velocity, are computed. A commonly-used evolutionary multi-objective optimization algorithm (NSGA-II) is then employed to find a set of trade-off solutions. The accuracy of the developed software (we called GOSpel) is demonstrated by matching the trajectories with known missions.

1 Introduction

The interplanetary mission design is a challenging task. These missions are complicated due to dynamics of our solar system. As spacecraft travels through our solar system it may encounter many celestial bodies, and may get influenced by their gravitational fi elds (swing-by of planets). These gravitational fi elds may be used in a constructive way to help in reducing energy requirement of a flight. Sending satellites to interplanetary trajectory is risky and expensive. There can be various trajectories which a spacecraft may follow. But there has to be an optimal trajectory which when followed, gives high performance boost either in energy requirement or in time required for the mission.

Genetic Algorithms (GAs) have been used for over 20 years in various applications of optimization. GAs are successfully applied in many complex real-world optimization problems where the function to be optimized is highly non-linear and discrete. In the recent past, they have been adapted very successfully in solving multi-objective optimization problems involving more than one conflicting objectives. Non-dominated sorting algorithm-II (NSGA-II) [7] is an example of such GA based multi-objective optimizers. In this paper, we develop NSGA-II-based trajectory optimization problems in a software, we called GOSpel. The time of window in which optimal solutions are sought, type of the transfer, choice of mission and information about the swing-by planets is accepted from the user. The practical limits on launch parameters like difference in flyby velocities, maximum and minimum bounds on number of days taken are also asked from the user. GA parameters, which become very relevant play an important role and need some tuning. The software displays a number of trade-off optimized solutions and allows user to investigate the trajectory through a graphical user interface.

2 Previous Studies on Interplanetary Trajectory Optimization

The celestial mechanics of the 'swing-by' is known to astronomers for at least 150 years. A lot of research work have been done in the area of Interplanetary Trajectory Optimization (IPTO), for both direct transfer and with swing-by of other planets. In 1925, Walter Hohmann [9] designed the transfer trajectory for two non intersecting orbits, which later has been used for direct transfer from one planet to another planet. Cornelisse [6] studied the various methods for computation of interplanetary trajectory and showed that interplanetary trajectories were most efficiently accomplished by the method of patched conics. Miele and Wang [10] presented fundamental properties of optimal orbital direct transfer using the cases of transfer from Earth orbit to Mars orbit and from Earth orbit to Venus orbit. They focused on compromised trajectories between flight time and propellant mass. Biesbroek and Ancarola [4] studied genetic algorithm setting for trajectory optimization. They used swing-by calculator [3] for their work for finding trajectory of rockets and interplanetary trajectories. Weeks [12] optimized flight time for interplanetary trajectory using GA and also studied effects of GA parameters. In 1973-74, Mariner 10 spacecraft was the first spacecraft to use the gravitational field of any planet. It used swing-by of Venus and Mercury to reach Mercury. Voyager1, launched on September 5 1977, visited Jupiter in 1979 and Saturn in 1980. Voyager 2, launched August 20 1977, visited Jupiter in 1979, Saturn in 1981 and Uranus in 1986 before making its closest approach to Neptune on August 25, 1989. In 1989, Galileo spacecraft used swing-by of Venus, Earth (two times) and Jupiter to reach to one of the moon of Jupiter. It also uses two swing-bys from other celestial bodies between Earth-Earth swing-by and Earth-Jupiter swing-by.

There are some softwares available for optimizing interplanetary trajectories. One of them is "Orbital Mechanics with Numerit PRO" [2]. The package contain Numerit Pro1 application that can be used to solve variety of technical problem in orbital mechanics, including interplanetary trajectory optimization. The major disadvantage of the software is that the user has to decide certain parameters like, to use swing-by or not, which planet to be used as swing-by and at what altitude etc. The software also uses grid search technique (exhaustive search) to optimize the trajectory. Another disadvantage is that, at most only one planet can be used for swing-by. Another software "Swing-By Calculator" provided by Jaquar Space Engineering [3] adds extra feature for performing multiple swing-bys. It is dependent on user choices like which planet to take swing-by and at what dates. In this paper, we try to overcome these deficiencies and develop a Genetically Optimized Spacecraft Launcher (GOSpel).

3 Proposed Approach with Swing-by

In flyby or swing-by assisted missions, a spacecraft first have to go to one or more flyby planets and then to the destination planet. This way there may exist a conflict between the energy requirement and the time to complete for the mission. Here, we formulate the above-mentioned problem into a multi-objective optimization problem and solve using the NSGA-II procedure [7]. The objective function considered here are (i) minimization of launch velocity and (ii) minimization of the total time of travel. Both the objectives have their own importance. The launch velocity is directly associated with the fuel (energy) requirement, which in turn effects the cost and technical aspects. By minimizing time of flight, one can achieve missions to complete quickly. Also in cases where we need to send a spacecraft for a rescue mission to another planet we want to reach to the planet at the earliest possible time.

The trajectory optimization problem involves a number of decision variables and constraints, a description of which requires us to first understand the transfer of spacecraft from one planet to another.

The standard orbital mechanics [5] uses parameters like state vectors and velocity maneuvers for fixing a trajectory. For computing a transfer from one planet to another, a patched conic model [5] is usually employed. In this model, the motion takes place along a plane. In practice, the transfer can involve swing-by planets or can be a direct one. Thus, when a swing-by is to be considered, the spacecraft may have to go through a plane change from one pair of planet transfer to the other. This requires the spacecraft to spend some energy for making a change in its motion from one plane to another. To take care of this additional energy, we add it in the computation of the initial launch velocity.

3.1 Direct Transfer

Let us now explain how to compute the motion between a pair of planets. Say, the spacecraft moves from first planet to the second planet. This involves knowing the location of both planets at the start and at the end when the spacecraft reaches the second planet. Moreover, assume that we fix a transfer time t for reaching second planet from the first one and investigate if such a transfer is possible from the location information of both planets. The Lambert's approach [8] helps us determine the velocity vectors required at the first (v_1) and second (v_2) planet in order to materialize such a transfer time. Lambert's approach involves an iterative procedure of adjusting the velocities so that the desired transfer time t is achieved. Thus, for a direct transfer, the departure date and transfer time are the two variables of the optimization problem.

3.2 Swing-by Transfer

Let us now discuss the swing-by case, involving at least one swing-by planet. It is clear that for S swing-by planets, there are $(S + 1)$ pairs of transfer needed. For a transfer time t_i for the i-th transfer, Lambert's approach can be used to find velocity vectors of the spacecraft v_{i-1}^+ ($+$ mean outgoing from the planet) and v_i^- ($-$ means incoming to the planet) near $(i - 1)$-th and i-th planets, respectively. Thus, for a transfer time t_i, the Lambert's approach computes a pair of velocity vectors of the spacecraft near the participating planets. Now, for the i-th swing-by planet, we have an incoming velocity v_i^- computed from the i-th transfer (with i-th planet as the second planet) and outgoing velocity v_i^+ computed from the $(i+1)$-th transfer (with i-th planet as the first planet). The difference between these two velocity vectors introduce a change in plane from one transfer to the other. This requires that the spacecraft generates some thrust so that the required change of plane is achieved. This energy will be taken into account by adding it to the launch energy objective. Thus, the departure date, S swing-by planets, and $(S+1)$ transfer times are the variables for an optimization problem.

For the swing-by case, the feasibility of an overall transfer from launch till final arrival planet needs to be checked. It is mentioned above that by Lambert's approach the incoming and outgoing velocity vectors of each swing-by planet can be computed for a given set transfer time values of each pair of successive planets. In order to have the overall transfer feasible, the difference between the incoming and outgoing speed ($|v_i^-|$ and $|v_i^+|$) of every swing-by planet must be as small as possible. In practice, we construct one equality constraint for each swing-by planet:

$$|v_i^+| - |v_i^-| = 0, \quad i = 1, 2, \ldots, S. \tag{1}$$

Since the above two velocities are computed from two consecutive transfer times (t_{i-1} and t_i), these transfer times can be adjusted so that the above equality constraint is met. Thus, for S swing-by planets, we shall have S such equality constraints involving $(S+1)$ speed values. This gives us some flexibility of choosing the speed values for a feasible overall transfer. However, there is a difficulty with this approach.

Recall that in the Lambert's approach, the velocity and location of spacecraft at two participating planets are the outcome and the departure date and transfer time are input parameters. Thus, by adjusting $(S+1)$ transfer time values and using the Lambert's approach S times (one for each transfer), we can try to come up with a set of $(S+1)$ velocity vectors which would satisfy all S equality constraints mentioned above. To convert the above problem into a root-finding problem, we introduce another equality constraint involving the altitude (h_i) of the spacecraft at the first swing-by planet. For the first swing-by planet, we introduce the following equality constraint:

$$h_1 - h_1^d = 0, \tag{2}$$

where h_1^d is the desired altitude of the first swing-by planet. For all other swing-by planets, ideally we should ensure that the altitude is positive, but in this study we consider negative altitude solutions as well by assuming them to be 'powered swing-bys'. We add an equivalent energy component in the launch velocity to take into account of not colliding with the swing-by planet.

For a given solution during optimization involving departure time and $(S+1)$ transfer times with known swing-by planets, we first attempt to investigate if the solution constitutes a feasible trajectory from departure planet to the destination planet through swing-by planets. If yes, we compute the overall transfer time and the required launch velocity as two objective values. In this case, all the above constraints are satisfied. Otherwise (when one or more of the above constraints are not satisfied), we attempt to repair the given solution by solving the root-finding problem using Newton-Raphson method involving $(S+1)$ variables (transfer times) and equations. The obtained transfer times will be, in general, different from what they were on the original solution. Then, we replace the original transfer time values with the calculated transfer time values which will make the solution feasible. If the calculated transfer time values are within the given lower and upper bounds of transfer time values, we accept the solution and compute the objective values, otherwise we declare the solution infeasible.

3.3 Handling Using NSGA-II

First, we discuss the representation scheme for the decision variables within the NSGA-II framework [7]. We fix a maximum of three swing-by planets, thereby leaving us with four options: (i) direct flight (no swing-by), (ii) one planet swing-by, (iii) two planet swing-by and (iv) three planet swing-by. We use a two-bit substring for representing these four options with `00`, `01`, `10` and `11`, respectively. Thereafter, we have three substrings of three bits each. Each three-bit substring represents a swing-by planet (one of the first eight planets of the solar system coded as `000` : Mercury, `001` : Venus, `010` : Earth, etc. Depending on the first two-bit substring dictating the number of swing-by planets we pick the corresponding planets from the string. These $2 + 3 \times 3$ or 11-bit strings give us information about which and how many planets are used in the trajectory determination.

The next set of 4 variables are coded as real-valued variables and represent transfer times between departure planet to first swing-by planet, first to second swing-by planet, second to third swing-by planet and third swing-by to arrival planet. Here again, depending on the number of swing-by planets (S) dictated by the first two-bit substring, we consider only the first $(S + 1)$ transfer times. A typical NSGA-II solution may look like the following:

`10 000 100 101` 16/6/2005 124 205 580 425

The solution signifies that there are two swing-by planets and they are the first planet (Mercury) and fifth planet (Jupiter) between departure and arrival planets (need not be represented in NSGA-II, as they are fixed for all feasible solutions). Thus, we ignore the third swing-by planet mentioned in the solution. The next decision variable is the departure date (16 June 2005). This date is actually represented using the Julian day (which is an integer value). The next four real-valued values are transfer times and we only pick the first three values as the transfer time between the departure and the first swing-by planet and so on. Once again, the transfer time of 425 is a useless parameter for this solution, since only two swing-bys are considered dictated by the first two-bit substring `10`.

In the case of direct transfers, only two variables (the departure date and the first real-parameter value indicating the transfer time) are used in the evaluation procedure. Thus for a single-planet swing-by six, for a two-planet swing-by eight and for three-planet swing-by all ten variables are to be considered.

Staring with the departure date and transfer time values in a NSGA-II string, incoming and outgoing speed values are calculated using Lambert's approach for each transfer. The transfer time values and the altitude of the first swing-by planet are adjusted by using the Newton-Raphson method till the equality constraints are satisfied

Table 1. Earth-Venus-Mercury trajectories using GOSpel and exhaustive search.

		Exhaustive Search	GOSpel
Earth Departure Date	(mm/dd/yy)	08/05/02	08/05/02
Venus Swing-By Date	(mm/dd/yy)	12/05/02	12/05/02
Mercury Arrival Date	(mm/dd/yy)	02/13/03	02/07/03
Altitude at Venus	(km)	-938.9	-978.84
Total Time	(Days)	192	186
Launch Velocity	(km/s)	2.79	2.78

using a small ϵ value. Thereafter, the original transfer time values are replaced with the ones computed using the Newton-Raphson method. Objective values are then computed for the solution. Variable bounds on transfer times are checked and any violation is assigned as the 'constraint violation' of the solution and the solution is declared infeasible.

With the above evaluation scheme, the NSGA-II procedure considers a population of solutions and emphasizes feasible over infeasible solutions, non-dominated solutions over dominated solutions and less-crowded solutions over crowded solutions. For details of NSGA-II procedure, readers are encouraged to refer [7].

We combine the evaluation scheme with NSGA-II and develop a user-friendly software for practice. The GA Optimized Spacecraft Launcher (GOSpel) software is capable of handling the following features:

- An option of direct or one to three swing-bys individually,
- An option of simultaneous consideration of direct or to a maximum of three planet swing-bys.
- A true optimization varying departure date over a large launch window as a real-valued parameter (and not with a finite step of one full day, as used in many commercial softwares)
- An option of flyby out of arrival planet or orbital around the arrival planet
- With an interactive and GUI-based window system of providing various options about departure planet, swing-by planets (if desired) and arrival planets, NSGA-II parameter update window and altitude constraint update window.

4 Proof-of-Principle Results

To demonstrate the correctness of our implementation of the trajectory optimization procedure and evaluation of solutions, we first apply our developed code to a number of known missions, taken from the web and literature. The comparison of our obtained solutions with those computed by other means is then performed.

4.1 Earth-Venus-Mercury Mission

First, we consider a Earth-to-Mercury mission with a possible swing-by from Venus. This problem was studied by using an exhaustive search procedure [11] for the minimization of launch velocity. For the years 2001 and 2002, the launch possibility and corresponding launch velocity needed for the mission to Mercury via Venus was calculated with a step size of one day for departure. The best solution found is shown in Table 1. To validate our procedure, we use GOSpel during this two-year departure window to find Pareto-optimal solution for the minimization of launch velocity and time of flight. We use the option for using one or no swing-by and the option of an orbital motion to the destination planet. A population of size 200 and a maximum generation of 200 are fixed. The GOSpel software uses the SBX operator with $p_c = 0.9$ and $\eta_c = 10$ and the polynomial mutation operator with $p_m = 1/n$ and $\eta_m = 20$. Figure 1 shows the corresponding frontier. It is interesting to note that there are two disconnected fronts: (i) trajectories with swing-by and (ii) trajectories with direct transfer. For minimum launch velocity trajectories, it is recommended to use the swing-by from Venus and for minimum time trajectories it is better to go straight to Mercury from Earth. Table 1 shows a closest solution to the exhaustively searched solution for the minimum launch velocity objective. The GOSpel solution is closer to the previously-reported solution. In fact, since no finite step is used in GOSpel, a better launch-velocity solution than the exhaustive search method (with a step size of one day) is found. The best launch velocity solution demands a slightly smaller value than the exhaustive search solution. The matching of our results with the exhaustive search solution by an independent study provides confidence to our developed software.

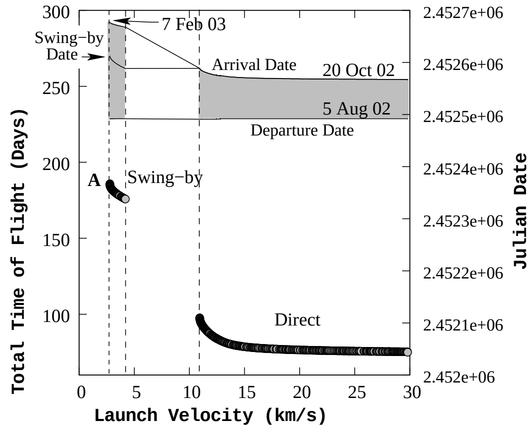

Fig. 1. Trade-off solutions for the Earth-Venus-Mercury mission using GOSpel.

Before we leave this proof-of-principle study, we also plot the departure, swing-by, and arrival dates of all obtained solutions by GOSpel. Figure 1 marks the Julian dates of these trajectories (values marked on the right axis). The following features of trajectories are gathered:

1. All Pareto-optimal missions must start at the same date: 5 October 2002, irrespective of whether the mission involves a swing-by or not.
2. With an increase in launch velocity requirement, the arrival becomes quicker. It seems that if departed from Earth on 5 October 2002, there exist a number of plausible missions trading-off launch velocity and travel time.

The use of an evolutionary multi-objective optimization algorithm to find a set of Pareto-optimal solutions allows one to look for such important information about the solutions.

Before executing this study, it would be difficult to predict that on a two-year long span of plausible departure dates, there exist one particular day (5 October 2002) which opens up enormous and optimal opportunities of several launching.

4.2 Earth-Mars-Venus-Mercury Mission

Table 2. Earth-Mars-Venus-Mercury trajectories. Dates are in mm/dd/yy.

	VSSC	GOSpel
Earth Departure Date	08/14/05	08/14/05
Mars swing-by Date	10/26/05	10/26/05
Mars: v_∞ incoming (km/s)	15.9737	15.9465
Mars: v_∞ outgoing (km/s)	15.7722	15.9465
Venus swing-by Date	02/01/06	01/31/06
Venus: v_∞ incoming (km/s)	8.7439	8.9958
Venus: v_∞ outgoing (km/s)	8.9459	8.9958
Mercury Arrival	03/31/06	03/31/06
Flight Time (Days)	229	228.326
Launch Velocity (km/s)	11.176	11.145

Next, we apply GOSpel and compare its results with another study performed by a commercial software, Swing-by Calculator (SC) [3] on a mission involving two planet swing-bys: Mars and Venus. The destination planet is Mercury and the departure window is kept within 1 Jan 2005 for a year. Table 2 shows the obtained SC result obtained for minimum time of flight. The dates of arrival at Mars and Venus and the corresponding arrival and departure velocities are also shown in the table. The GOSpel solutions are shown in Figure 2 for both objectives. In this case, we allow only two-planet swing-by trajectories to be considered. Thus, direct or one-planet swing-by option is not considered. All solutions found involve two swing-bys, but providing a trade-off between time of flight and energy requirement. The solution on the Pareto-optimal front closest to the SC solution is tabulated in Table 2. The comparison of both solutions again indicates the accuracy of GOSpel procedure.

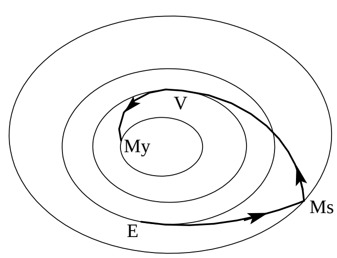

Fig. 2. Trade-off solutions for the Earth-Mars-Venus-Mercury mission using GOSpel.

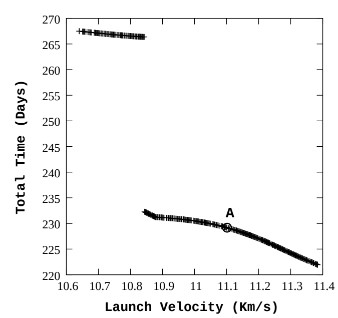

Fig. 3. Trajectory for the specific Earth-Mars-Venus-Mercury mission shown in the table.

Interestingly, the SC solution does not seem to be the minimum-time solution. The figure shows that there exists a solution with a smaller time of flight. Figure 3 shows the trajectory of the two-planet swing-by solution of the solution shown in the table. The travel from earth to Mars (outward) and then back to Venus (inward) and finally to Mercury is interesting.

4.3 Direct Transfer

Next, we consider a direct transfer scenario from Earth to Mars. For this purpose, we use solutions from two softwares Numerit and SC. The departure dates within 1 June 2013 to 1 June 2014 are considered. This scenario is an example test problem reported in users' manual of the NUMERIT software. Both Numerit and SC softwares use a grid search strategy in which solutions at a step of one day is considered one at a time and the solution having the minimum launch velocity is found. The table shows that SC solution is better than the Numerit solution. Next, we apply GOSpel with a population size of 100 and run till 300 generations. The two extreme solutions are shown in table. It is interesting to note that the minimum launch velocity solution obtained by GOSpel is almost similar to that obtained by SC. Both Numerit and SC do not allow to find a solution corresponding to minimum time of flight. The minimum time solution obtained by GOSpel takes only 50 days to reach Mars from Earth, by requiring about seven times more launch velocity.

Table 3. Earth-Mars direct transfer trajectories.

	NUMERIT	SC	GOSpel	
			Min. Vel.	Min. Time
Departure Date	01/10/14	12/05/13	12/06/13	03/20/14
Arrival Date	08/19/14	09/26/14	09/27/14	05/10/14
Flight Time (Days)	221.29	295	295.132	50
Launch Vel. (km/s)	7.65	6.2436	6.244	41.7006

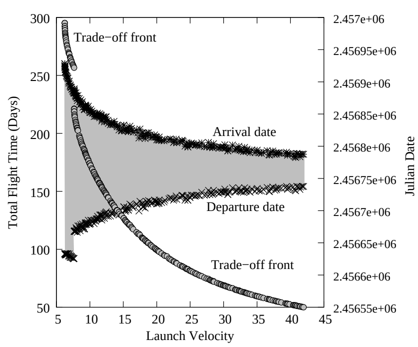

Fig. 4. Trade-off solutions for the Earth-Mars direct mission using GOSpel.

Figure 4 shows the Pareto-optimal frontier obtained by GOSpel. The arrival and departure times for each of these solutions are also shown in the same figure. In this case, the departure date gradually increases towards the upper limit for a quicker time of flight. Missions starting in January of 2014 results in smaller energy requirements but at the expense of flight time and missions in February/March of 2014 requires smaller time of flight but at the expense of larger energy requirement. Such is a trade-off often occurs in interplanetary missions and the studies of this paper amply demonstrates the ability of GOSpel in finding a number of them. It then becomes a matter of higher-level decision-making task to choose one solution for implementation, which we do not discuss in this paper.

4.4 Cassini Mission

Next, we a mission having three swing-by planets. We found that the Cassini-Huygens mission has four swing-bys [1]. But since our software is limited to a maximum of three swing-by planets, we has the first three of four swing-by planets in this study. The mission type is set to be a flyby type at the destination planet. Thus, the complete mission for the case is departure from Earth, swing-by from Venus, another swing-by from Venus, third swing-by from Earth and the final arrival to Jupiter. A typical trajectory (taken from [1]), GOSpel and SC solutions are compared in Table 4. From the table, it can be observed that solution found by GOSpel and SC are non-dominated GOSpel solution but time taken are more close to actual mission dates.

Table 4. Earth-Venus-Venus-Earth-Jupiter transfer (part of Cassini mission) using SC and GOSpel.

	Web [1]	GOSpel	SC
Departure Date	10/15/97	10/15/97	10/29/97
Venus Date	04/26/98	05/19/98	05/11/98
Earth-to-Venus Time (Days)	193	216.318	194
Venus Date	06/24/99	06/22/99	06/26/99
Venus-to-Venus Time (Days)	424	399	411
Earth Date	08/18/99	08/17/99	08/18/99
Venus-to-Earth Time (Days)	55	55.940	53
Jupiter Arrival Date	12/30/00	12/22/00	02/02/01
Earth-to-Jupiter Time (Days)	500	493.46	534
Total Flight Time (Days)	1172	1164.72	1192
Launch Vel. (km/s)	NA	6.805	4.46

5 Earth-Mercury Mission

Here, we consider three different optimization studies: (i) direct (ii) swing-by from Venus and (iii) optional direct or Venus swing-by. The departure time window considered here is 21/9/2002 till 22/9/2002 (just a day). 200 population members are used for 200 generations.

Figure 5 shows the Pareto-optimal front obtained by a direct transfer. The reason for a break in the continuity in the Pareto-optimal front is due to the availability of two different opportunity windows for an optimal mission. Next, we apply GOSpel on the same departure date window and obtain solutions with forced swing-bys. Figure 5 also shows the Pareto-optimal solutions for this case. Due to the swing-by option, the required launch velocity is much smaller than that obtained with the direct transfer.

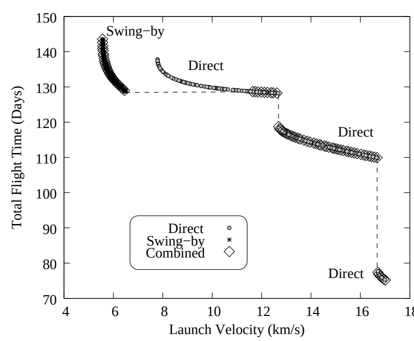

Fig. 5. Comparison of three transfer cases for Earth-Venus-Mercury mission.

Finally, we consider both options (direct and swing-by) in GOSpel and obtain a combined Pareto-optimal front. Interestingly, this front is found to be identical to a combined non-dominated front of the two fronts obtained earlier. The Pareto front is divided into two discrete parts. One part belong to flyby cases where swing-by planet is Venus. The other part shows direct transfer. From Figure 5, it can be said that there exists a clear conflict, whether to take a swing-by or not. If swing-by is taken then, smaller launch velocity is required, whereas with direct transfer the flight time is less. The figure shows that a saving of about 3 km/s launch velocity occurs between the two type of transfers with a mission of 130 days.

6 Conclusions

In this paper, we have discussed the development of a multi-objective optimization software (GOSpel) for finding optimal interplanetary trajectories between any two planets for a dual minimization of travel time and launch velocity which is directly related to the fuel consumption. The software is capable of considering a maximum of three swing-by of intermediate planets to assist in reducing the fuel consumption. The use Pareto-optimality concept and genetic algorithms has demonstrated that the proposed approach can be used to find a set of trade-off solutions which match with the existing solutions of known missions. Thereafter, the developed code is applied to a number of complex case studies and interesting solutions have been obtained. This paper has amply shown the usefulness and flexibility of such a code for real-time application of EMO for interplanetary trajectory optimization.

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