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Jean-Baptiste Caillau, Bilel Daoud

## To cite this version:

Jean-Baptiste Caillau, Bilel Daoud. Minimum time control of the restricted three-body problem. 2011. hal-00599216v2

## HAL Id: hal-00599216 <br> https://hal.science/hal-00599216v2

Preprint submitted on 5 Aug 2011 (v2), last revised 10 Apr 2012 (v4)

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# Minimum time control of the restricted three-body problem 

J.-B. Caillau*<br>B. Daoud ${ }^{\dagger}$

July 2010


#### Abstract

The minimum time control of the circular restricted three-body problem is considered. Controllability is proved on an adequate submanifold. Singularities of the extremal flow are studied by means of a stratification of the switching surface. Properties of homotopy maps in optimal control are framed in a simple case. The analysis is used to perform continuations on the two parameters of the problem: The ratio of masses, and the magnitude of the control.


Keywords. three-body problem, minimum time control, control-affine systems, homotopy, conjugate points

MSC classification. $49 \mathrm{~K} 15,70 \mathrm{Q} 05$

## 1 Problem statement

The control of two bodies was addressed in [14. The first body exerted a central force on the second, which was an artificial satellite of negligible mass whose thrust was the control. The resulting controlled Kepler equation was shown to be controllable, and minimization of time was studied (see also the subsequent papers [13, [8]). The present paper is the continuation of this work. Now under the influence of two primary bodies, the artificial satellite is still endowed with a thrust. The motion of the two primaries, not influenced by the third negligible mass, is supposed to be circular. Among the numerous previous studies on space missions in the three-body framework, one has to mention the pioneering work of [21], and more recently of [18]. These approaches are purely celestial mechanical ones and rely on a fine knowledge of the dynamical system with three bodies or more. More on the control side see,e.g., [3] for numerical results using direct methods, 6] for a preliminary study on stabilization, and 22, 20] for a combination of control and dynamical system techniques. The model we consider is the following [27].

[^0]Let $\mu \in(0,1)$ be the ratio of the primary masses, and let $Q_{\mu}=\mathbf{C} \backslash\{-\mu, 1-$ $\mu\}$. For $q \in Q_{\mu} \subset \mathbf{C} \simeq \mathbf{R}^{2}$ and positive thrust magnitude $\varepsilon$, define the controlled circular restricted three-body problem (planar model) according td ${ }^{1}$

$$
\ddot{q}(t)-2 \bar{\partial} \Omega_{\mu}(q(t))+2 i \dot{q}(t)=\varepsilon u(t), \quad|u(t)|=\sqrt{u_{1}^{2}(t)+u_{2}^{2}(t)} \leq 1
$$

Here, $(q, \dot{q}) \in X_{\mu}=T Q_{\mu} \simeq Q_{\mu} \times \mathbf{C}$ are Cartesian coordinates in a rotating frame ( $q=e^{-i t} \xi$ where $\xi$ is the position vector in a fixed frame) and

$$
\Omega_{\mu}(q)=\frac{1}{2}|q|^{2}+\frac{1-\mu}{|q+\mu|}+\frac{\mu}{|q-1+\mu|}
$$

Another choice of coordinates consists in letting $X_{\mu}=T^{*} Q_{\mu}$, taking the cotangent bundle instead to write the drift in Hamiltonian form. Let $p=\dot{q}+i q$ and let

$$
\begin{aligned}
J_{\mu}(q, \dot{q}) & =\frac{1}{2}|\dot{q}|^{2}-\Omega_{\mu}(q) \\
& =\frac{1}{2}|p|^{2}+p \wedge q-\frac{1-\mu}{|q+\mu|}-\frac{\mu}{|q-1+\mu|}
\end{aligned}
$$

be the Jacobian integral. Then,

$$
\dot{q}(t)=\frac{\partial J_{\mu}}{\partial p}(q(t), p(t)), \quad \dot{p}(t)=-\frac{\partial J_{\mu}}{\partial q}(q(t), p(t))+\varepsilon u(t), \quad|u(t)| \leq 1
$$

More compactly,

$$
\dot{x}(t)=F_{0}(x(t))+\varepsilon u_{1}(t) F_{1}(x(t))+\varepsilon u_{2}(t) F_{2}(x(t)), \quad|u(t)| \leq 1,
$$

with, in $(q, p)$ coordinates for $x \in X_{\mu}$,

$$
F_{0}(q, p)=\overrightarrow{J_{\mu}}, \quad F_{1}(q, p)=\frac{\partial}{\partial p_{1}}, \quad F_{2}(q, p)=\frac{\partial}{\partial p_{2}}
$$

where $\overrightarrow{J_{\mu}}=\left(\nabla_{p} J_{\mu},-\nabla_{q} J_{\mu}\right)$ is the symplectic gradient. When $\mu=0$, we get a two-body problem: $J_{0}=E-C$ with energy and momentum respectively equal to

$$
\begin{gathered}
E=\frac{1}{2}|\dot{\xi}|^{2}-\frac{1}{|\xi|}=\frac{1}{2}|\dot{q}|^{2}-\frac{1}{2}|q|^{2}-q \wedge \dot{q}-\frac{1}{|q|} \\
C=\xi \wedge \dot{\xi}=q \wedge \dot{q}+|q|^{2}
\end{gathered}
$$

Restricting to the elliptic domain, $X_{0} \cap\{E<0, C>0\}$, another system of coordinates tailored for the analysis is obtained using orbital elements describing the geometry of the osculating ellipse. Let $n>0$ be the mean motion ( $a^{3} n^{2}=1$ if $a$ the semi-major axis), $\left(e_{x}, e_{y}\right) \in \mathbf{D}$ be the eccentricity vector (where $\mathbf{D}$ is the open unit ball of $\mathbf{R}^{2}$ ), and $l \in \mathbf{R}$ the longitude (the class modulo $2 \pi$ of $l$ is just the polar angle in the fixed $\left(\xi_{1}, \xi_{2}\right)$-frame). Alternatively, one can use polar coordinates $(e, \theta) \in(0,1) \times \mathbf{S}^{1}$ for the eccentricity on the (pointed) Poincaré disk $\mathbf{D}(\theta$ is called the argument of pericenter $)$. In this system, $x=(n, e, \theta, l)$,

$$
F_{0}(x)_{\mid \mu=0}=\frac{n W^{2}}{\left(1-e^{2}\right)^{3 / 2}} \frac{\partial}{\partial l}, \quad W=1+e \cos \tau
$$

[^1]\[

$$
\begin{gathered}
\widetilde{F}_{1}(x)=\frac{\sqrt{1-e^{2}}}{n^{1 / 3}}\left(-\frac{3 n e \sin \theta}{1-e^{2}} \frac{\partial}{\partial n}+\sin \tau \frac{\partial}{\partial e}-\cos \tau \frac{1}{e} \frac{\partial}{\partial \theta}\right) \\
\widetilde{F}_{2}(x)=\frac{\sqrt{1-e^{2}}}{n^{1 / 3}}\left(-\frac{3 n W}{1-e^{2}} \frac{\partial}{\partial n}+\left(\cos \tau+\frac{e+\cos \tau}{W}\right) \frac{\partial}{\partial e}+\left(\sin \tau+\frac{\sin \tau}{W}\right) \frac{1}{e} \frac{\partial}{\partial \theta}\right)
\end{gathered}
$$
\]

where $\tau=l-\theta$. We have also used a feedback on the control to express the control not in the $\left\{\partial / \partial \dot{\xi}_{1}, \partial / \partial \dot{\xi}_{2}\right\}$ frame but in the radial-orthoradial one, so

$$
\widetilde{F}_{1}(\xi, \dot{\xi})=\frac{\xi_{1}}{|\xi|} \frac{\partial}{\partial \dot{\xi}_{1}}+\frac{\xi_{2}}{|\xi|} \frac{\partial}{\partial \dot{\xi}_{2}}, \quad \widetilde{F}_{2}(\xi, \dot{\xi})=-\frac{\xi_{2}}{|\xi|} \frac{\partial}{\partial \dot{\xi}_{1}}+\frac{\xi_{1}}{|\xi|} \frac{\partial}{\partial \dot{\xi}_{2}}
$$

The criterion under consideration is the final time, and the paper is organized as follows.

Section 2 is devoted to controllability. Whatever the bound on the control, it is proven that admissible trajectories between arbitrary points exist provided the Jacobian constant is smaller than the one given for some equilibrium point of the uncontrolled system. The structure of optimal controls is addressed in Section 3, refining the results of [14]. In particular the role of peri and apocenters with respect to global bounds on the number of switchings of the control is emphasized, in connection with averaging of the system. The system has indeed two parameters: The bound of the control, $\varepsilon$, which can be taken very small with low-thrust applications in mind [23] thus leading to averaging; and the ratio of masses, $\mu$, on which a continuation à la Poincaré may be performed to embed the two-body problem into a three-body one. This idea is the key to solving the problem as explained in Section 4 where continuations both with respect to $\mu$ and $\varepsilon$ are considered. The peculiarity of homotopy maps in optimal control is then illustrated in a simple framework, in relation to second order optimality conditions.

## 2 Controllability

The drift has five equilibrium points, $L_{1}(\mu), \ldots, L_{5}(\mu)$, known as Lagrange points [27, whose position depends on $\mu$. The points $L_{1}, L_{2}$ and $L_{3}$ are the colinear or Euler points, the points $L_{4}$ and $L_{5}$ form two equilateral triangles with $-\mu$ and $1-\mu$. When $\mu=0, L_{1}=L_{2}=1, L_{3}=-1$, and $L_{4}=\exp (i \pi / 3), L_{5}=-\exp (i \pi / 3)$ (all belong to $\mathbf{S}^{1}$ which is a continuum of equilibrium points in this particular case). The Jacobian $J_{\mu}$ is the only first integral of the non-integrable uncontrolled system. Every level set $\left\{J_{\mu}=j\right\}$ projects onto $\Omega_{\mu}(q)+j=|\dot{q}|^{2} / 2 \geq 0$ in the $\left(q_{1}, q_{2}\right)$-space, defining the Hill regions where the free motion has to take place (see Fig. 11). Let $j_{i}(\mu)=J_{\mu}\left(L_{i}(\mu)\right)$, $i=1, \ldots, 5$ denote the Jacobian constants of these points. For $\mu \in(0,1)$, $j_{2}<j_{1}<j_{3}<j_{4}=j_{5}$ (these values all degenerate to $-3 / 2$ when $\mu$ goes to zero). The open subset $\left\{x \in X_{\mu} \mid J_{\mu}(x)<j_{1}(\mu)\right\}$ has two connected components, and we denote by $X_{\mu}^{1}$ the component containing $L_{2}(\mu)$ (see Fig. 2p. Below we recall the basic facts needed to prove controllability on this subset.

Consider a smooth ${ }^{2}$ control-affine system on a manifold $X$,

$$
\dot{x}(t)=F_{0}(x(t))+\sum_{i=1}^{m} u_{i} F_{i}(x(t)), \quad u(t) \in U \subset \mathbf{R}^{m},
$$

[^2]

Figure 1: Lagrange points and associated Hill regions, $\mu \in(0,1)$. The (dashed) forbidden regions of motion (complementary to the Hill regions) monotonically decrease as the Jacobian constant tends to $J_{\mu}\left(L_{4}\right)=J_{\mu}\left(L_{5}\right)$ (then disappear past this value) and opens up past $J_{\mu}\left(L_{1}\right)$.
such that $U$ is a neighbourhood of the origin. The attainable set (by piecewise constant controls) from $x_{0} \in X$ depends only on the drift, $F_{0}$, and on the distribution $\mathscr{D}$ spanned by the vector fields $F_{1}, \ldots, F_{m}$. It is the set of points obtained by compositions of flows,

$$
e^{t_{p} G_{p}} \circ \cdots \circ e^{t_{1} G_{1}}\left(x_{0}\right), \quad G_{i} \in F_{0}+\mathscr{D}, \quad t_{i} \geq 0
$$

with $t_{i}$ small enough for the composition to be defined. Now, if $\mathscr{F}$ is an arbitrary subsheaf of $\mathscr{C}^{\infty}$ vector fields on $X$, assuming for simplicity all $F \in \mathscr{F}$ complete, define the subgroup $\mathscr{G}$ of the diffeomorphisms of $X$ generated by the one parameter subgroups $\exp t F, t \in \mathbf{R}, F \in \mathscr{F}$. According to the orbit theorem [1, 25], the orbit of $\mathscr{G}$ through $x_{0}$ is an immersed submanifold of $X$ whose tangent space is

$$
T_{x} \mathscr{G}\left(x_{0}\right)=\operatorname{Span}_{x}\{(\operatorname{Ad} \varphi) F, \varphi \in \mathscr{G}, F \in \mathscr{F}\}
$$

In the previous expression, the adjoint action $\operatorname{Ad} \varphi$ maps $F$ to its conjugate, $\varphi \cdot F \cdot \varphi^{-1}\left(=\left(\varphi^{-1}\right)_{*} F\right)$ with diffeomorphisms and vector fields acting linearly on $\mathscr{C}^{\infty}(X, \mathbf{R})$ (defining automorphisms and derivations, respectively). In coordinates,

$$
(\operatorname{Ad} \varphi) F_{\mid x}=\left[\varphi^{\prime}(x)\right]^{-1} F(\varphi(x)), \quad x \in X
$$

Restricting to the $\mathscr{C}^{\omega}$-category, the adjoint action and the exponential commute in the sense that, for arbitrary vector fields $F, G$,

$$
\left(\operatorname{Ad} e^{t F}\right) G_{\mid x}=\left(e^{t \mathrm{ad} F}\right) G_{\mid x}=\sum_{n \geq 0} \frac{t^{n}}{n!}\left(\operatorname{ad}^{n} F\right) G_{\mid x}, \quad x \in X
$$

where $(\operatorname{ad} F) G$ is the Lie bracket $[F, G]=F \cdot G-G \cdot F$, and recursively for $\mathrm{ad}^{n}$. In this case, the orbit theorem then simply reads

$$
T_{x} \mathscr{G}\left(x_{0}\right)=\operatorname{Lie}_{x} \mathscr{F}
$$

If the vector fields are not complete, $\mathscr{G}$ is just a pseudo-group 17 but the conclusion of the orbit theorem - which is local-is preserved. Coming back to control-affine systems, assuming that

$$
\begin{equation*}
\operatorname{Lie}_{x}\left\{F_{0}, F_{1}, \ldots, F_{m}\right\}=T_{x} X, \quad x \in X \tag{1}
\end{equation*}
$$

and that the drift $F_{0}$ is recurrent ${ }^{3}$ it can be proven that compositions with the flow of $-F_{0}$ can be added when computing the attainable set (see [16). So the attainable set is equal to the orbit of the pseudo-group associated with $\left\{F_{0}, F_{1}, \ldots, F_{m}\right\}$. Because of the orbit theorem and of (11), this orbit has to be the whole manifold (supposed to be connected). In the control-affine three-body case, the rank condition holds as is clear from

Lemma 1. A second order controlled system on $\mathbf{R}^{m}$,

$$
\ddot{q}(t)+g(q(t), \dot{q}(t))=u(t)
$$

is a control-affine system on $\mathbf{R}^{2 m}$ with an involutive distribution $\mathscr{D}$ and a drift $F_{0}$ such that $\left\{F_{1}, \ldots, F_{m},\left[F_{0}, F_{1}\right], \ldots,\left[F_{0}, F_{m}\right]\right\}$ has maximum rank.

Proof. As a first order system,

$$
F_{0}(q, \dot{q})=\dot{q}_{1} \frac{\partial}{\partial q_{1}}+\cdots+\dot{q}_{m} \frac{\partial}{\partial q_{m}}-g_{1}(q, \dot{q}) \frac{\partial}{\partial \dot{q}_{1}}-\cdots-g_{m}(q, \dot{q}) \frac{\partial}{\partial \dot{q}_{m}}
$$

and $F_{i}=\partial / \partial \dot{q}_{i}$ (so $\mathscr{D}$ is clearly involutive). Then

$$
\left[F_{0}, F_{i}\right]=-\partial / \partial q_{i} \quad \bmod \mathscr{D}
$$

so the rank is maximum.
Applying the lemma to the planar three-body problem ( $m=2$ ), one obtains controllability in the following way.

Theorem 1. For any $\mu \in(0,1)$, for any positive $\varepsilon$, the circular restricted three-body problem is controllable on $X_{\mu}^{1}$.
Proof. Let $x_{0}, x_{f}$ in $X_{\mu}^{1}$, and let $j$ be strictly smaller than the Jacobian constants of both endpoints. Set $\widetilde{X}_{\mu}^{1}=X_{\mu}^{1} \cap\left\{J_{\mu}>j\right\}$. Outside a subset of zero measure associated with initial conditions generating collisions $(q=-\mu$ or $1-\mu)$, the drift is a complete Hamiltonian vector field whose exponential is defined for all times and is a volume preserving bijection in $(q, p)$ coordinates. By definition, $\widetilde{X}_{\mu}^{1}$ which is a union of level sets of the Hamiltonian $J_{\mu}$ is invariant with respect to the exponential. For $x=(q, p) \in \widetilde{X}_{\mu}^{1}$,

$$
j+\Omega_{\mu}(q)<\frac{1}{2}|p-i q|^{2}<j_{1}(\mu)+\Omega_{\mu}(q)
$$

Then, for a fixed $q$, the volume of the $q$-section of $\widetilde{X}_{\mu}^{1}$ is bounded by $2 \pi\left(j_{1}(\mu)-j\right)$ as is clear integrating with respect to $\mathrm{d} p_{1} \mathrm{~d} p_{2}=\rho \mathrm{d} \rho \mathrm{d} \alpha($ set $p-i q=\rho \exp (i \alpha))$.

[^3]

Figure 2: Projection of the open submanifold $X_{\mu}^{1}$ in the $\left(q_{1}, q_{2}, J_{\mu}\right)$-space. The boundary of the volume is an apparent contour generated by the projection. It is the zero velocity set. Above each interior point there is an $\mathbf{S}^{1}$-fibre corresponding to the argument of $\dot{q}$. For $\mu \in(0,1), j_{2}<j_{1}$ and $X_{\mu}^{1}$ is connex.

Since the projection on the $\left(q_{1}, q_{2}\right)$-space of $\widetilde{X}_{\mu}^{1}$ is also bounded, the $\mathrm{d} q \wedge \mathrm{~d} p$ measure of $\widetilde{X}_{\mu}^{1}$ is finite (Fubini). We conclude as in [24] that almost every point of $\widetilde{X}_{\mu}^{1}$ is recurrent by Poincaré theorem. Controllability on $\widetilde{X}_{\mu}^{1}$ follows and implies the existence of a trajectory joining $x_{0}$ to $x_{f}$, which in turn implies controllability on $X_{\mu}^{1}$.

Remark 1. In the two-body case, $\mu=0$, controllability still holds on $X_{0}^{1}$, the bounded component of $\left\{J_{0}<j_{1}(0)=-3 / 2\right\}$. Each section of $X_{0}^{1}$ by a level set $\left\{J_{0}=j\right\}$ is a pointed disk containing bounded, hence periodic, trajectories of of the uncontrolled system. The energy is negative but, as $J_{0}=E-C, X_{0}^{1}$ contains both direct $(C>0)$, retrograde $(C<0)$ and collision orbits $(C=0)$. In contrast, the controllability result in 14 was obtained on the elliptic domain, $X_{0} \cap\{E<0, C>0\}$, using the periodicity of the drift and excluding collisions (a sign had then to be imposed on the momentum so that the manifold be connex).
Remark 2. In order to obtain an existence result for minimum time, one has to prove that minimizing trajectories remain into a fixed compact (which depends on the prescribed boundary conditions). Then, from any minimizing sequence
one can extract a converging subsequence whose limit is an admissible trajectory by virtue of the convexity of the velocity field $\left\{F_{0}(x)+\varepsilon u_{1} F_{1}(x)+u_{2} F_{2}(x),|u| \leq\right.$ $1\}$ for all $x \in X$ (Filippov theorem). One of the difficulties due to collisions is so to give bounds on the distance to the singularities, $-\mu$ and $1-\mu$.

## 3 Singularities of the extremal flow

Let $u:\left[0, t_{f}\right] \rightarrow \mathbf{R}^{2}$ be a measurable time-minimizing control of the controlaffine system

$$
\dot{x}(t)=F_{0}(x(t))+u_{1} F_{1}(x(t))+u_{2} F_{2}(x(t)), \quad u_{1}^{2}(t)+u_{2}^{2}(t) \leq 1
$$

defined on a manifold $X$ of dimension four. Let $x$ denote the associated Lipschitz trajectory. Pontryagin maximum principle asserts that $x$ is the projection of a Lipschitzian curve, the extremal $z=(x, p):\left[0, t_{f}\right] \rightarrow T^{*} X \backslash\{0\}$, valued in the cotangent bundle minus the null section. In coordinates, there is a nonpositive scalar $p^{0}$ such that, a.e. on $\left[0, t_{f}\right]$,

$$
\dot{x}(t)=\frac{\partial H}{\partial p}(x(t), u(t), p(t)), \quad \dot{p}(t)=-\frac{\partial H}{\partial x}(x(t), u(t), p(t))
$$

with Hamiltonian $H(x, u, p)=p^{0}+H_{0}(x, p)+u_{1} H_{1}(x, p)+u_{2} H_{2}(x, p)$ and Hamiltonian lifts $H_{i}(x, p)=\left\langle p, F_{i}(x)\right\rangle, i=0,1,2$. Moreover, the maximization condition holds a.e.,

$$
H(x(t), u(t), p(t))=\max _{|v| \leq 1} H(x(t), v, p(t))
$$

As a result, $H$ is a.e. equal to a constant (zero, here, because the final time is free) along ( $x, u, p$ ), and

$$
u(t)=\frac{\psi(t)}{|\psi(t)|}
$$

whenever the switching function $\psi(t)=\left(H_{1}, H_{2}\right)(x(t), p(t))$ does not vanish. The switching surface is

$$
\Sigma=\left\{(x, p) \in T^{*} X \mid H_{1}(x, p)=H_{2}(x, p)=0\right\}
$$

and we make the following assumption on the distribution $\mathscr{D}$ spanned by $F_{1}$ and $F_{2}$. Let

$$
\begin{aligned}
D(x) & =\operatorname{det}\left(F_{1}(x), F_{2}(x),\left[F_{0}, F_{1}\right](x),\left[F_{0}, F_{2}\right](x)\right) \\
D_{1}(x) & =\operatorname{det}\left(F_{1}(x), F_{2}(x),\left[F_{1}, F_{2}\right](x),\left[F_{0}, F_{2}\right](x)\right) \\
D_{2}(x) & =\operatorname{det}\left(F_{1}(x), F_{2}(x),\left[F_{0}, F_{1}\right](x),\left[F_{1}, F_{2}\right](x)\right)
\end{aligned}
$$

we assume that
(i) $D_{1}^{2}(x)+D_{2}^{2}(x)<D^{2}(x), x \in X$.

The following results refine those in [14] (see also [8]).

Proposition 1. Let $u$ be a piecewise continuous optimal control. Then $u$ is bang-bang and, at a switching point $\bar{t}$,

$$
\alpha(\bar{t}+)-\alpha(\bar{t}-)=2 \beta+\pi, \quad \beta=\arcsin \frac{\left\{H_{1}, H_{2}\right\}(\bar{z})}{\sqrt{\left\{H_{0}, H_{1}\right\}^{2}(\bar{z})+\left\{H_{0}, H_{2}\right\}^{2}(\bar{z})}},
$$

where $\alpha$ is the angle of the control and $\bar{z}=(x(\bar{t}), p(\bar{t}))$ the associated value of the extremal.

Lemma 2. For any $u \in \mathbf{R}^{2}$ such that $|u| \leq 1$, vector fields $F_{1}, F_{2},\left[F_{0}, F_{1}\right]-$ $u_{2}\left[F_{1}, F_{2}\right]$ and $\left[F_{0}, F_{2}\right]+u_{1}\left[F_{1}, F_{2}\right]$ form a frame. For $z=(x, p) \in \Sigma \backslash\{0\}$,

$$
\left\{H_{1}, H_{2}\right\}^{2}(z)<\left\{H_{0}, H_{1}\right\}^{2}(z)+\left\{H_{0}, H_{2}\right\}^{2}(z)
$$

Proof. Computing,

$$
\begin{gathered}
\operatorname{det}\left(F_{1}(x), F_{2}(x),\left[F_{0}, F_{1}\right](x)-u_{2}\left[F_{1}, F_{2}\right](x),\left[F_{0}, F_{2}\right](x)+u_{1}\left[F_{1}, F_{2}\right](x)\right)= \\
D(x)-u_{2} D_{1}(x)+u_{1} D_{2}(x), \quad x \in X, \quad u \in \mathbf{R}^{2} .
\end{gathered}
$$

Hence, for $|u| \leq 1,\left\{F_{1}, F_{2},\left[F_{0}, F_{1}\right]-u_{2}\left[F_{1}, F_{2}\right],\left[F_{0}, F_{2}\right]+u_{1}\left[F_{1}, F_{2}\right]\right\}$ form a frame by virtue of (i). Let $z=(x, p)$ belong to $\Sigma, p \neq 0$. Then for an arbitrary $u \in \mathbf{R}^{2},|u| \leq 1$,

$$
\left[\begin{array}{l}
\left\langle p,\left[F_{0}, F_{1}\right](x)\right\rangle \\
\left\langle p,\left[F_{0}, F_{2}\right](x)\right\rangle
\end{array}\right]+\left\langle p,\left[F_{1}, F_{2}\right](x)\right\rangle\left[\begin{array}{r}
-u_{2} \\
u_{1}
\end{array}\right] \neq\left[\begin{array}{l}
0 \\
0
\end{array}\right],
$$

since $p$ would otherwise be zero. Whence the conclusion on the Poisson brackets as $\left\langle p,\left[F_{0}, F_{1}\right](x)\right\rangle=\left\{H_{0}, H_{1}\right\}(z)$ and so on.

Proof (of Proposition 1). The switching function is almost everywhere differentiable and, at a Lebesgue point,

$$
\begin{aligned}
\dot{\psi}_{1}(t) & =\left\{H_{0}, H_{1}\right\}(z(t))-u_{2}(t)\left\{H_{1}, H_{2}\right\}(z(t)) \\
\dot{\psi}_{2}(t) & =\left\{H_{0}, H_{2}\right\}(z(t))+u_{1}(t)\left\{H_{1}, H_{2}\right\}(z(t)) .
\end{aligned}
$$

So $\dot{\psi}$ is as $u$ piecewise continous and has left and right limits everywhere. If $\bar{z}=z(\bar{t})$ belongs to $\Sigma \backslash\{0\}$, neither $\dot{\psi}(\bar{t}-)$ nor $\dot{\psi}(\bar{t}+)$ vanish according to the previous lemma. The time $\bar{t}$ is so an isolated zero and one has $u=\psi /|\psi|$ outside finitely many switching points. Left and right limits of the control angle at $\bar{t}$ verify

$$
\left\{H_{1}, H_{2}\right\}(\bar{z})-\sin \alpha\left\{H_{0}, H_{1}\right\}(\bar{z})+\cos \alpha\left\{H_{0}, H_{2}\right\}(\bar{z})=0
$$

which, thanks to the lemma, has exactly two solutions with the predicted discontinuity.

Assuming moreover that
(ii) $\mathscr{D}$ is involutive,
we get
Corollary 1 ([14). Any optimal control is piecewise continuous with finitely many switches all of angle $\pi$ (" $\pi$-singularities").

Proof. When $\mathscr{D}$ is involutive, the switching function is $\mathscr{C}^{1}$ since the bracket $\left\{H_{1}, H_{2}\right\}$ vanish at switching points (one has $\left[F_{1}, F_{2}\right]=0 \bmod \mathscr{D}$ ). All zeros are isolated by the previous argument and $\beta=0$, whence the conclusion.

We finally add the assumption that
(iii) $F_{0} \notin \operatorname{Span}\left\{F_{1}, F_{2},\left[F_{0}, F_{2}\right]\right\}$,
and define

$$
\Sigma_{0}=\Sigma \cap\left\{(x, p) \in T^{*} X \mid F_{0}(x) \in \operatorname{Span}_{x}\left\{F_{1}, F_{2},\left[F_{0}, F_{2}\right]\right\}\right\}
$$

Remark 3. Assumptions (i) and (ii) put together are equivalent to saying that $\mathscr{D}$ is involutive and that $F_{1}, F_{2},\left[F_{0}, F_{1}\right]$ and $\left[F_{0}, F_{2}\right]$ form a frame. These properties depend only on the distribution (and the drift), not on a particular choice of basis of $\mathscr{D}$-in contrast with (iii).

Theorem 2 (14). In the normal case, there cannot be consecutive switchings in $\Sigma_{0}$. In particular, if $\Sigma=\Sigma_{0}$, any normal optimal control has at most one switching which is a $\pi$-singularity.

Proof. According to (i), there are continous scalar functions $\lambda_{1}, \lambda_{2}$ on $X$ such that

$$
F_{0}=\lambda_{1}\left[F_{0}, F_{1}\right]+\lambda_{2}\left[F_{0}, F_{2}\right] \quad \bmod \mathscr{D}
$$

At a switching point $z(\bar{t})=(x(\bar{t}), p(\bar{t})) \in \Sigma_{0}$,

$$
H(x(\bar{t}), u(\bar{t}), p(\bar{t}))=-p_{0}=\lambda_{2}(x(\bar{t}))\left\{H_{0}, H_{2}\right\}(z(\bar{t}))=\lambda_{2}(x(\bar{t})) \dot{\psi}_{2}(\bar{t})
$$

In the normal case, $p_{0}<0$, so

$$
\lambda_{2}\left(x\left(\bar{t}_{1}\right)\right) \dot{\psi}_{2}\left(\bar{t}_{1}\right) \lambda_{2}\left(x\left(\bar{t}_{2}\right)\right) \dot{\psi}_{2}\left(\bar{t}_{2}\right)=p_{0}^{2}>0
$$

if we assume that $\bar{t}_{1}<\bar{t}_{2}$ are consecutive such switching times. Because of (iii), $\lambda_{2}$ never vanishes; by continuity its sign is constant so $\dot{\psi}_{2}\left(\bar{t}_{1}\right) \dot{\psi}_{2}\left(\bar{t}_{2}\right)>0$, whence the contradiction.

Thanks to Lemma 1, these results apply to the problem under consideration: The circular restricted three-body has bang-bang time-minimizing controls with finitely many $\pi$-singularities. A remarkably simple geometric interpretation of $\Sigma_{0}$ is obtained when restricting to a two-body system, $\mu=0$. This case is not only important in itself as it also corresponds to the initial and final phases of a typical three-body low-thrust transfer. Such a trajectory resembles a heteroclinic trajectory connecting periodic orbits around each one of the primaries (see Fig. 4). We use for the analysis the geometric coordinates and the radialorthoradial frame introduced in Section 1. We assume the eccentricity positive, $0<e<1$, to obviate the singularity of these coordinates at circular orbits. With $x=(n, e, \theta, l) \in \mathbf{R}_{+}^{*} \times(0,1) \times \mathbf{S}^{1} \times \mathbf{R}($ and $\tau=l-\theta), p=\left(p_{n}, p_{e}, p_{\theta}, p_{l}\right) \in\left(\mathbf{R}^{4}\right)^{*}$, we set

$$
\alpha=-\frac{3 n}{1-e^{2}} p_{n}, \quad \beta=p_{e}, \quad \gamma=\frac{p_{\theta}}{e}, \quad c=\cos \tau, \quad s=\sin \tau
$$

so $\Sigma$ is defined by the following algebraic system:

$$
\alpha e s+\beta s-\gamma c=0
$$

$$
\begin{gathered}
\alpha(1+e c)+\beta\left(c+\frac{e+c}{1+e c}\right)+\gamma\left(s+\frac{s}{1+e c}\right)=0 \\
c^{2}+s^{2}=1
\end{gathered}
$$

Proposition 2. The switching surface $\Sigma$ for $\mu=0$ is stratified as follows:
(i) If $\gamma=0$, either $(\alpha, \beta)=(0,0)$, or $s=0$ and $\alpha, \beta$ belong to the union of the two distinct lines

$$
(1+e) \alpha+2 \beta=0, \quad(1-e) \alpha-2 \beta=0 .
$$

(ii) If $\gamma \neq 0$, $s$ is not zero and $\alpha, \beta$ are uniquely determined.

Proof. The algebraic system in $\alpha, \beta$

$$
\begin{aligned}
\alpha e s+\beta s & =\gamma c \\
\alpha(1+e c)+\beta\left(c+\frac{e+c}{1+e c}\right) & =-\gamma\left(s+\frac{s}{1+e c}\right),
\end{aligned}
$$

has determinant

$$
\left|\begin{array}{rr}
e s & s \\
1+e c & c+\frac{e+c}{1+e c}
\end{array}\right|=-\frac{s\left(1-e^{2}\right)}{1+e c}
$$

whence the result.
Proposition 3. In the two-body case $\mu=0$, the subset $\Sigma_{0}$ is the stratum $\{s=0\}$ of $\Sigma$. Accordingly,

$$
\Sigma \cap\left\{p_{\theta}=0\right\}=\Sigma_{0} \cup\left\{\left(p_{n}, p_{e}, p_{\theta}\right)=(0,0,0)\right\} .
$$

Proof. Using the fact that $F_{0} \in \operatorname{Span}\{\partial / \partial l\}$ and that, for smooth functions $f, g$

$$
\left[f F_{0}, g \widetilde{F}_{2}\right]=f g\left[F_{0}, \widetilde{F}_{2}\right] \quad \bmod \operatorname{Span}\left\{F_{0}, \widetilde{F}_{2}\right\}
$$

the condition $\operatorname{det}\left(F_{0}, \widetilde{F}_{1}, \widetilde{F}_{2},\left[F_{0}, \widetilde{F}_{2}\right]\right)=0$ is equivalent to

$$
\left|\begin{array}{rrrr}
0 & e s & 1+e c & -e s \\
0 & s & c+\frac{e+c}{1+e c} & -s-\frac{s\left(1-e^{2}\right)}{(1+e c)^{2}} \\
0 & -c & s+\frac{s}{1+e c} & c+\frac{e+c}{(1+e c)^{2}} \\
1 & 0 & 0 & 0
\end{array}\right|=0
$$

that is to

$$
s=0 \quad \text { or } \quad e(1+e c)=0
$$

so the conclusion follows.
Geometrically, $s=\sin \tau=0$ (that is, $l-\theta=0 \bmod \pi$ ) corresponds to peri and apocenters. The importance of the stratum $\Sigma \cap\left\{p_{\theta}=0\right\}$ comes from the analysis of the system when the control magnitude $\varepsilon$ goes to zero (low-thrust case).

When the control is small, not only the time but also the angular length (longitude) needed to connect two Keplerian orbits in the two-body model becomes large. It thus makes sense to use averaging to analyze the behaviour of extremal trajectories. In the case of the minimization of the $\mathrm{L}^{2}$-norm of the control (energy minimization), this approach goes back to [15] (see also [11] for a recent treatment of this question). One first uses the fact that, in the planar model, the drift only acts on the longitude,

$$
\dot{l}(t)=\omega(x(t)), \quad \omega(x)=\frac{n W^{2}}{\left(1-e^{2}\right)^{3 / 2}}, \quad W=1+e \cos \tau
$$

to set $l$ as the new time. In this new parameterization, minimum time extremals are integral curves of the maximized Hamiltonian

$$
\hat{H}(l, \hat{x}, \hat{p})=\frac{p^{0}}{\omega(l, \hat{x})}+\varepsilon \sqrt{\hat{H}_{1}^{2}(l, \hat{x}, \hat{p})+\hat{H}_{2}^{2}(l, \hat{x}, \hat{p})}
$$

with $\hat{x}=(n, e, \theta), \hat{p}=\left(p_{n}, p_{e}, p_{\theta}\right)$, and

$$
\begin{aligned}
\hat{H}_{1}^{2}(l, \hat{x}, \hat{p})+\hat{H}_{2}^{2}(l, \hat{x}, \hat{p}) & =\frac{\left(1-e^{2}\right)^{4}}{n^{8 / 3} W^{4}}\left\{\frac{9 n^{2}}{\left(1-e^{2}\right)^{2}}\left(1+2 e \cos \tau+e^{2}\right) p_{n}^{2}\right. \\
& -\frac{12 n}{1-e^{2}}(e+\cos \tau) p_{n} p_{e} \\
& \left.+\left[1+\frac{2(e+\cos \tau)}{W} \cos \tau+\frac{(e+\cos \tau)^{2}}{W^{2}}\right] p_{e}^{2}\right\}+\cdots
\end{aligned}
$$

where the dots indicate terms in $p_{\theta}^{2}, p_{n} p_{\theta}$ and $p_{e} p_{\theta}$. The averaged Hamiltonian is

$$
\begin{equation*}
\overline{\hat{H}}(\hat{x}, \hat{p})=\frac{1}{2 \pi} \int_{0}^{2 \pi} \hat{H}(l, \hat{x}, \hat{p}) \mathrm{d} l . \tag{2}
\end{equation*}
$$

Proposition 4. The argument of pericenter $\theta$ is a cyclic variable of the averaged system. On the stratum $\left\{p_{\theta}=0\right\}$, the integral (2) is hyperelliptic of genus 2 .
Proof. As is clear from the whole dynamics in geometric coordinates (see Section 11), only the difference $\tau=l-\theta$ appear in $\hat{H}$. Averaging with respect to $l$-or equivalently to $\tau$-kills terms in $\theta$ and $p_{\theta}$ becomes a linear first integral. On $\left\{p_{\theta}=0\right\}$ then,

$$
\sqrt{\hat{H}_{1}^{2}+\hat{H}_{2}^{2}}=\frac{1}{W^{3}} \sqrt{R(\cos \tau)}
$$

where $R$ is a degree 3 polynomial with coefficients depending nonlinearly on $\hat{x}$ and quadratically on $\hat{p}$. Setting for instance $u=\cos \tau$ leads to

$$
\int \frac{\mathrm{d} u}{1-u^{2}} \sqrt{\left(1-u^{2}\right) R(u)}
$$

which is an integral parameterized by a genus 2 hyperelliptic curve.
Remark 4. For circular targets (which are of great practical importance in two or three-body control), the transversality condition is $p_{\theta}=0$. The previous analysis then suggests that, for small control magnitudes, $p_{\theta}$ should also remain small so that the switching structure be close to the one on $\Sigma \cap\left\{p_{\theta}=0\right\}$ :

Assuming there are no trivial switchings $\left(p_{n}, p_{e}, p_{\theta}\right)=0$, one would get a global bound on the number of $\pi$-singularities (at most one). Nevertheless, one should notice that, if $p_{\theta}$ is small but not zero, the switchings does not belong to $\Sigma_{0}$ according to Propositions 2 and 3 Moreover, when studying the convergence of the system towards the averaged one, one should take into accout the lack of regularity due to the radicand vanishing (see also [5] for jn alternative approach to averaging). For instance,

$$
f(z)=\int_{0}^{\pi / 2} \sqrt{\sin ^{2} l+z^{2}} \mathrm{~d} l=|z| E\left(-i z^{-1}\right)
$$

where $E$ is the complete elliptic integral of second kind. Such a function has a $z^{2} \log |z|$ singularity at the origin and is not $\mathscr{C}^{2}$ (logarithmic branch on the second derivative).

## 4 Homotopy

Consider a control problem with smooth data on an $n$-manifold $X$,

$$
\dot{x}(t)=f(x(t), u(t)), \quad u(t) \in U
$$

with cost

$$
\int_{0}^{t_{f}} f^{0}(x(t), u(t)) \mathrm{d} t \rightarrow \min
$$

and prescribed boundary conditions

$$
x(0)=x_{0}, \quad x\left(t_{f}\right)=x_{f} .
$$

For the sake of simplicity $t_{f}$ is supposed to be fixed, but the analyis below can be drawn with appropriate changes for free final time as well. We also suppose that $U$ is a manifold without boundary. In coordinates, this is assuming that $u$ belongs to some open subset of $\mathbf{R}^{m}$, where $m$ is the dimension of $U$. Let $\bar{u}:\left[0, t_{f}\right] \rightarrow U$ be a measurable and essentially bounded control, and let $\bar{x}:\left[0, t_{f}\right] \rightarrow X$ be the resulting trajectory. Pontryagin maximum principle implies that there exists a nonpositive constant $\bar{p}^{0}$ and a Lipschitz covector function $\bar{p}:\left[0, t_{f}\right] \rightarrow\left(\mathbf{R}^{n}\right)^{*}$, not both zero, so that in coordinates on $T^{*} X$,

$$
\dot{\bar{x}}(t)=\frac{\partial H}{\partial p}(\bar{x}(t), \bar{u}(t), \bar{p}(t)), \quad \dot{\bar{p}}(t)=-\frac{\partial H}{\partial x}(\bar{x}(t), \bar{u}(t), \bar{p}(t)),
$$

and

$$
H(\bar{x}(t), \bar{u}(t), \bar{p}(t))=\max _{v \in U} H(\bar{x}(t), v, \bar{p}(t))
$$

a.e. on $\left[0, t_{f}\right]$. Here,

$$
H(x, u, p)=p^{0} f^{0}(x, u)+\langle p, f(x, u)\rangle
$$

We assume that, on a neighbourhood of the extremal $(\bar{x}, \bar{p})$, the maximized Hamiltonian

$$
(x, p) \mapsto \max _{v \in U} H(x, u, p)
$$

is well defined and smooth; then $(\bar{x}, \bar{p})$ is an integral curve of the maximized function (see [1]), still denoted $H$ (but now depending only on $x$ and $p$ ). We finally make the Legendre regularity assumption that, uniformly on $\left[0, t_{f}\right]$,

$$
\nabla_{u u}^{2} H(\bar{x}(t), \bar{u}(t), \bar{p}(t)) \leq-\alpha I_{m}
$$

for some $\alpha>0$. As a consequence, there must exist in a neighbourhoud of the extremal a smooth implicit function $u(x, p)$ solving the first order necessary condition $\nabla_{u} H=0$ such that $\bar{u}(t)=u(\bar{x}(t), \bar{p}(t))$ and $H(x, p)=H(x, u(x, p), p)$. Summarizing, $\bar{p}(0) \in\left(\mathbf{R}^{n}\right)^{*}$ is a zero of the shooting function ${ }^{4}$

$$
p_{0} \mapsto x\left(t_{f}, x_{0}, p_{0}\right)-x_{f},
$$

where the exponential mapping

$$
\exp _{x_{0}}:\left(t, p_{0}\right) \mapsto x\left(t, x_{0}, p_{0}\right)
$$

sends a given $p_{0}$ to the $x$-projection of the integral curve at $t$ of the maximized Hamiltonian. Both functions are well defined and smooth on neighbourhoods of $\bar{p}(0)$ and $\left(t_{f}, \bar{p}(0)\right)$, respectively. A time $t_{c}$ is conjugate to 0 along $(\bar{x}, \bar{p})$ whenever $\bar{p}(0)$ is a critical point of $p_{0} \mapsto \exp \left(t_{c}, p_{0}\right)$. The critical value $x_{c}=\exp \left(t_{c}, \bar{p}(0)\right)$ is the corresponding conjugate point. These notions are related to necessary or sufficient second order conditions of optimality [1, 7].

The endpoint mapping

$$
F_{t_{f}, x_{0}}: u \mapsto \hat{x}\left(t_{f}, x_{0}, u\right)
$$

is well defined and smooth on a neighbourhood in $\mathrm{L}^{\infty}\left(\left[0, t_{f}\right], U\right)$ of the (class of) $\bar{u}$ and maps a control to the solution at $t_{f}$ of the augmented system $\left(\hat{x}=\left(x^{0}, x\right)\right)$

$$
\begin{aligned}
\dot{x}^{0}(t) & =f^{0}(x(t), u(t)), \quad \text { a.e. on }\left[0, t_{f}\right] \\
\dot{x}(t) & =f(x(t), u(t)), \quad x^{0}(0)=0, \quad x(0)=x_{0}
\end{aligned}
$$

Pontryagin maximum principle implies that $\bar{u}$ is a critical point ${ }^{5}$ of the endpoint mapping: $\operatorname{Im} F_{t_{f}, x_{0}}^{\prime}(\bar{u})$ has codimension in $\mathbf{R}^{n}$. If we assume that $\bar{u}$ is a corank one critical point, and moreover that it is analytical (with analytical data for the problem as well), the absence of conjugate time in $\left(0, t_{f}\right)$ is necessary for $\mathrm{L}^{\infty}$-local optimality ${ }^{6}$ Conversely, replacing the corank one and analyticity conditions by the assumption that the extremal is normal ( $p_{0}<0$ ), the absence of conjugate time on $\left(0, t_{f}\right]$ is sufficient for $\mathscr{C}^{0}$-local optimality ${ }^{7}$

Having in mind these connections with second order conditions in optimal control (see also [9, 26), we consider a one-parameter smooth Hamiltonian,

$$
H: \mathbf{R}^{2 n} \times \mathbf{R} \ni(x, p, \lambda) \mapsto H(x, p, \lambda) \in \mathbf{R}
$$

[^4]Given a positive final time $t_{f}$ and an initial condition $x_{0}$, we define the shootinglike homotopy function

$$
h\left(p_{0}, \lambda\right)=x\left(t_{f}, x_{0}, p_{0}, \lambda\right)
$$

that maps $\left(p_{0}, \lambda\right)$ to the coordinate $x$ of the solution at $t_{f}$ of

$$
\dot{x}(t)=\frac{\partial H}{\partial p}(x(t), p(t), \lambda), \quad \dot{p}(t)=-\frac{\partial H}{\partial x}(x(t), p(t), \lambda)
$$

with initial conditions $x(0)=x_{0}, p(0)=p_{0}$. By restricting it if necessary, we may assume that its domain of definition, $\Omega \subset \mathbf{R}^{n+1}$, is open and made only of regular points of $h$ so that

$$
\operatorname{rank} h^{\prime}\left(p_{0}, \lambda\right)=n, \quad\left(p_{0}, \lambda\right) \in \Omega
$$

As a consequence, the level set $\{h=0\}$ is a one-dimensional submanifold of $\mathbf{R}^{n+1}$ called the path of zeros. Typically, one knows a zero of $h(., \lambda)$ for, say, $\lambda=0$, and wants to follow this path to reach if possible a zero for a target value of the parameter, $\lambda=1$. For any $c=\left(p_{0}, \lambda\right) \in \Omega$, $\operatorname{dim} \operatorname{Ker} h^{\prime}(c)=1$ so one can define the (tangent) vector $T(c)$ as being the unique - up to orientationunit vector in the kernel. The orientation is chosen so that the nonvanishing determinant

$$
\operatorname{det}\left[\begin{array}{c}
h^{\prime}(c) \\
{ }^{t} T(c)
\end{array}\right]
$$

has constant sign on each connected component of $\Omega$. This provides a parameterization by arc length of the connected components of $\{h=0\}$ which can be practically computed by integrating the following differential equation [2] (with $\left.{ }^{\prime}=\mathrm{d} / \mathrm{d} s\right)$ :

$$
c^{\prime}(s)=T(c(s)), \quad c(0)=c_{0} \in\{h=0\}
$$

The aim is to classify each component up to diffeomorphisms, knowing that there are only two possibilities [19]: It is diffeomorphic either to $\mathbf{R}$ or to $\mathbf{S}^{1}$.

In such a parameterization, a point $c(\bar{s})=\left(p_{0}(\bar{s}), \lambda(\bar{s})\right)$ in $\{h=0\}$ is a turning point when $\lambda^{\prime}(\bar{s})=0$. This is equivalent to saying that

$$
\operatorname{rank} \frac{\partial x}{\partial p_{0}}\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right)=n-1
$$

that is to saying that $t_{f}$ is a conjugate time for $\lambda=\lambda(\bar{s})$ (and that $p_{0}(\bar{s})$, $x\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right)$ are the corresponding critical point and value, respectively). A turning point of order one, that is such that $\lambda^{\prime \prime}(\bar{s}) \neq 0$, actually results in a change of variation on $\lambda$, hence the name. We define $\bar{c}=c(\bar{s}) \in\{h=0\}$ to be a first turning point (along the path starting at $c(0))$ if, for all $s \in[0, \bar{s})$, the curve $t \mapsto x\left(t, x_{0}, p_{0}(s), \lambda(s)\right)$ has no conjugate time on $\left(0, t_{f}\right]$.

Theorem 3. Let $c(\bar{s}) \in\{h=0\}$ be a first turning point of order one such that

$$
\frac{\partial^{2} x}{\partial t \partial p_{0}}\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right) \pitchfork\left\{\frac{{ }^{c} \partial x}{\partial p_{0}}\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right)\right\}^{\perp}
$$

Then, for $s>\bar{s},|s-\bar{s}|$ small enough, there exist conjugate times in $\left(0, t_{f}\right)$.

Remark 5. In the transversality assumption of the theorem, $\partial x / \partial p_{0}$ is of rank $n-1$ at the point, so its cofactor matrix is not zero and defines a hyperplane in the Euclidean set of square matrices of order $n$ endowed with the Frobenius scalar product. Let $\delta z=(\delta x, \delta p)$ be the $(2 n \times n)$-matrix valued solution of the linearized system

$$
\delta \dot{z}(t)=\vec{H}^{\prime}\left(z\left(t, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right)\right) \cdot \delta z(t), \quad \delta z(0)=\left[\begin{array}{c}
0 \\
I_{n}
\end{array}\right]
$$

where $z\left(., x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right)$ denotes the integral curve of the Hamiltonian system for $\lambda=\lambda(\bar{s})$ and initial condition $\left(x_{0}, p_{0}(\bar{s})\right)$. Then

$$
\frac{\partial^{2} x}{\partial t \partial p_{0}}\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right)=\delta \dot{x}\left(t_{f}\right)
$$

and the assumption reads $\delta \dot{x}\left(t_{f}\right) \pitchfork\left\{{ }^{c} \delta x\left(t_{f}\right)\right\}^{\perp}$.
We recall that, at a corank one critical point $\bar{x}$ of a smooth function $g: \mathbf{R}^{n} \rightarrow$ $\mathbf{R}^{n}$, one can define (up to a scalar) the intrinsic second order derivative [4] as

$$
\bar{\mu} g^{\prime \prime}(\bar{x})_{\mid \operatorname{Ker} g^{\prime}(\bar{x}) \times \operatorname{Ker} g^{\prime}(\bar{x})} \in \mathscr{L}_{2}\left(\operatorname{Ker} g^{\prime}(\bar{x}), \operatorname{Ker} g^{\prime}(\bar{x}) ; \mathbf{R}\right) \simeq \mathbf{R}
$$

where $\bar{\mu} \in\left(\mathbf{R}^{n}\right)^{*}$ is any nonzero covector with kernel $\operatorname{Im} g^{\prime}(\bar{x})$. The critical point is said nondegenerate provided this quantity is not zero.

Lemma 3. The turning point $c(\bar{s})$ is of order one if and only if $p_{0}(\bar{s})$ is a nondegenerate corank one critical point of $p_{0} \mapsto h\left(p_{0}, \lambda(\bar{s})\right)$.
Proof. Differentiating twice $h(c(s))=0$, one gets

$$
h^{\prime \prime}(c(\bar{s})) \cdot\left(c^{\prime}(\bar{s}), c^{\prime}(\bar{s})\right)+h^{\prime}(c(\bar{s})) \cdot c^{\prime \prime}(\bar{s})=0
$$

As $c^{\prime}(\bar{s})=\left(p_{0}^{\prime}(\bar{s}), 0\right), p_{0}^{\prime}(\bar{s})$ generates the kernel of $\partial h / \partial p_{0}\left(p_{0}(\bar{s}), \lambda(\bar{s})\right)$ and

$$
\frac{\partial h}{\partial p_{0}}(c(\bar{s})) \cdot p_{0}^{\prime \prime}(\bar{s})+\frac{\partial h}{\partial \lambda}(c(\bar{s})) \cdot \lambda^{\prime \prime}(\bar{s})=-\frac{\partial^{2} h}{\partial p_{0}^{2}}(c(\bar{s})) \cdot\left(p_{0}^{\prime}(\bar{s}), p_{0}^{\prime}(\bar{s})\right)
$$

Multiplying both sides by any nonzero $\bar{\mu}$ whose kernel coincides with the image of $\partial x / \partial p_{0}\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right)$, one gets

$$
\bar{\mu} \frac{\partial h}{\partial \lambda}(c(\bar{s})) \cdot \lambda^{\prime \prime}(\bar{s})=-\bar{\mu} \frac{\partial^{2} h}{\partial p_{0}^{2}}(c(\bar{s})) \cdot\left(p_{0}^{\prime}(\bar{s}), p_{0}^{\prime}(\bar{s})\right)
$$

At the regular point $c(\bar{s}) \in \Omega, \partial h / \partial \lambda$ is transverse to the image of $\partial h / \partial p_{0}$. So $\bar{\mu} \partial h / \partial \lambda(c(\bar{s})) \neq 0$, and $\lambda^{\prime \prime}(\bar{s})=0$ if and only if the intrinsic second derivative vanishes.
Remark 6. The order one assumption thus puts some restriction on

$$
\frac{\partial^{2} x}{\partial p_{0}^{2}}\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right) .
$$

This is a condition of order three (involving third order derivatives of the Hamiltonian).

Lemma 4. Let $\bar{x}$ be a corank one critical point of a smooth function $g: \mathbf{R}^{n} \rightarrow$ $\mathbf{R}^{n}$. Then $\bar{x}$ is degenerate if and only if

$$
\left(\operatorname{det} g^{\prime}\right)^{\prime}(\bar{x})=0 \quad \text { on } \quad \operatorname{Ker} g^{\prime}(\bar{x})
$$

Proof. Let $h \in \mathbf{R}^{n}$; one has

$$
\left.\left(\operatorname{det} g^{\prime}\right)^{\prime}(\bar{x}) \cdot h=\operatorname{tr} \widetilde{\left(g^{\prime}(\bar{x})\right.} \cdot g^{\prime \prime}(\bar{x}) \cdot h\right)
$$

Since $g^{\prime}(\bar{x})$ is of rank $n-1$, one can find a nonzero vector $\bar{\xi} \in \operatorname{Ker} g^{\prime}(\bar{x})(r e s p$. covector $\bar{\mu}$ with kernel $\left.\operatorname{Im} g^{\prime}(\bar{x})\right)$ such that the adjugate matrix

$$
\widetilde{g^{\prime}(\bar{x})}=\bar{\xi} \bar{\mu} .
$$

Thus,

$$
\begin{aligned}
\left(\operatorname{det} g^{\prime}\right)^{\prime}(\bar{x}) \cdot h & =\sum_{j=1}^{n} \operatorname{tr}\left(\bar{\xi} \bar{\mu} \frac{\partial g^{\prime}}{\partial x_{j}}(\bar{x})\right) h_{j} \\
& =\sum_{j=1}^{n} \bar{\mu} \frac{\partial g^{\prime}}{\partial x_{j}}(\bar{x}) \bar{\xi} h_{j} \\
& =\bar{\mu} g^{\prime \prime}(\bar{x})(\bar{\xi}, h)
\end{aligned}
$$

In particular, for $h=\bar{\xi} \in \operatorname{Ker} g^{\prime}(\bar{x})$,

$$
\left(\operatorname{det} g^{\prime}\right)^{\prime}(\bar{x}) \cdot \bar{\xi}=\bar{\mu} g^{\prime \prime}(\bar{x})(\bar{\xi}, \bar{\xi})
$$

whence the conclusion.
Remark 7. Under the assumptions of the lemma, $\chi(x, \mu)=\operatorname{det}\left(\mu I_{n}-g^{\prime}(x)\right)$ has root $\mu=0$ for $x=\bar{x}$, with algebraic multiplicity $k \leq n$ (while the geometric multiplicity of 0 , as an eigenvalue of $g^{\prime}(\bar{x})$, is one). By Malgrange preparation theorem, there are smooth scalar functions $a_{0}, \ldots, a_{k-1}$ and $b$ such that, in the neighbourhood of $(\bar{x}, 0)$,

$$
\chi(x, \mu)=b(x, \mu)\left(\mu^{k}+a_{k-1}(x) \mu^{k-1}+\cdots+a_{0}(x)\right)
$$

and $a_{0}(\bar{x})=\cdots=a_{k-1}(\bar{x})=0, b(\bar{x}, 0) \neq 0$. Accordingly,

$$
\left(\operatorname{det} g^{\prime}\right)^{\prime}(\bar{x})=b(\bar{x}, 0) a_{0}^{\prime}(\bar{x})
$$

The nondegeneracy at $\bar{x}$ is then equivalent to the statement that $\bar{x}$ is not a critical point of $a_{0}$, plus that $f$ and $a_{0}$ are transverse at $\bar{x}$. The quantity $a_{0}$ can be interpretated as a smooth (and signed) singular value of $f^{\prime}$ when $x$ is varied in the neighbourhood of $\bar{x}$, as is clear from the following example. Take $g\left(x_{1}, x_{2}\right)=\left(x_{2}, x_{1}^{2} / 2\right) ; \bar{x}=(0,0)$ is a nondegenerate corank one critical point. In a small enough neighbourhood of $\bar{x}$, the smallest singular value of

$$
g^{\prime}(x)=\left[\begin{array}{rr}
0 & 1 \\
x_{1} & 0
\end{array}\right]
$$

is $\sigma(x)=\left|x_{1}\right|$, which is not differentiable at the critical point. In contrast, $a_{0}(x)=-x_{1}$ is smooth and provides the information needed to check nondegeneracy.

Proof (of Theorem 3). Define the extended homotopy

$$
\widetilde{h}\left(p_{0}, \lambda, t_{c}\right)=\left(x\left(t_{f}, x_{0}, p_{0}, \lambda\right), \operatorname{det} \frac{\partial x}{\partial p_{0}}\left(t_{c}, x_{0}, p_{0}, \lambda\right)\right) .
$$

By assumption, the point $\left(p_{0}(\bar{s}), \lambda(\bar{s}), t_{f}\right)$ belongs to $\{\widetilde{h}=0\}$, and is regular. Indeed, $h^{\prime}$ is of rank $n$ at $c(\bar{s}) \in \Omega$, and

$$
\frac{\partial}{\partial t_{c}} \operatorname{det} \frac{\partial x}{\partial p_{0}}\left(t_{c}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right)_{\mid t_{c}=t_{f}}=\left(\frac{{ }^{c} \partial x}{\partial p_{0}} \left\lvert\, \frac{\partial^{2} x}{\partial t \partial p_{0}}\right.\right)\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right)
$$

is not zero so the rank of $\widetilde{h}^{\prime}$ at $\left(c(\bar{s}), t_{f}\right)$ is $n+1$. The extended homotopy is therefore well defined and regular in a neighbourhood of $\left(p_{0}(\bar{s}), \lambda(\bar{s}), t_{f}\right)$. Keeping the same parameterization by arc length on $\{\widetilde{h}=0\}$, we have $t_{c}(\bar{s})=t_{f}$. Since $c(\bar{s})$ is a first turning point, it is enough to prove that $t_{c}^{\prime}(\bar{s}) \neq 0$ (then, necessarily, $t_{c}^{\prime}(\bar{s})<0$-there would otherwise be conjugate times in $\left(0, t_{f}\right)$ for $s<\bar{s})$. As $\lambda^{\prime}(\bar{s})=0, p_{0}^{\prime}(\bar{s})$ belongs to $\operatorname{Ker} \partial x / \partial p_{0}\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right)$, and

$$
\frac{\partial}{\partial p_{0}} \operatorname{det} \frac{\partial x}{\partial p_{0}}\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right) \cdot p_{0}^{\prime}(\bar{s})+\frac{\partial}{\partial t_{c}} \operatorname{det} \frac{\partial x}{\partial p_{0}}\left(t_{f}, x_{0}, p_{0}(\bar{s}), \lambda(\bar{s})\right) \cdot t_{c}^{\prime}(\bar{s})=0 .
$$

The turning point being of order one, the first term in this sum is nonzero as a consequence of the two lemmas. Using again the transversality assumption, we are able to conclude that $t_{c}^{\prime}(\bar{s}) \neq 0$.

In addition to turning points, there are two other issues on homotopy. First, when the connected component of the path considered is diffeomorphic to $\mathbf{R}$, boundary points (if any) are critical points of $h$. The classification of points in $\partial \Omega$ starts with the following result which is a simple consequence of Morse lemma.

Proposition 5 ([2]). Let $\bar{c} \in\{h=0\}$ be a nondegenerate hyperbolic corank one critical point of $h$. Then, there are coordinates $d_{1}, \ldots, d_{n+1}$ such that, in the neighbourhood of $\bar{c},\{h=0\}$ is equal to

$$
d_{1}^{2}-d_{2}^{2}=0, \quad d_{3}=\cdots=d_{n+1}=0 .
$$

In this case, we have a critical point jointly in $p_{0}, \lambda$ and the intrinsic second order derivative is, up to a scalar,

$$
\bar{\mu} h^{\prime \prime}(\bar{c})_{\mid \operatorname{Ker} h^{\prime}(\bar{c}) \times \operatorname{Ker} h^{\prime}(\bar{c})} \in \mathscr{L}_{2}\left(\operatorname{Ker} h^{\prime}(\bar{c}), \operatorname{Ker} h^{\prime}(\bar{c}) ; \mathbf{R}\right) \simeq \operatorname{Sym}(2, \mathbf{R})
$$

where $\bar{\mu} \in\left(\mathbf{R}^{n}\right)^{*}$ is any nonzero covector with kernel $\operatorname{Im} h^{\prime}(\bar{c})$. Hyperbolicity means that this order 2 symmetric matrix is nondegenerate with eigenvalues of opposite signs. As a consequence, the path of zeros is locally made of two smooth curves intersecting transversally, resulting in a bifurcation. The last issue is due to global features in parametric optimal control. For a given value $\lambda_{0}$ of the parameter, one has to compare the costs associated to zeros in each connected component of $\{h=0\} \cap\left\{\lambda=\lambda_{0}\right\}$. Each zero of the shooting homotopy function defines an extremal and global solutions, if any, are those giving the infimum of the cost among them. In the three-body problem, the topology of the state manifold, $X_{\mu}=T^{*} Q_{\mu}$, comes into play; $Q_{\mu}$ has the topology of the eight curve,
$\pi_{1}\left(Q_{\mu}\right)=\mathbf{Z} * \mathbf{Z}$, and a heuristic classification of extremals based on homology is proposed in 12 .

Two homotopies are used to compute numerically minimum time trajectories of the restricted three-body problem. A continuation on the ratio of masses, $\mu$, is first considered. In practice, the isolated contacts with the codimension two switching surface are neglected, and we restrict the computation to smooth extremals without $\pi$-singularities. This yields regularity of the $\mu$-parameterized minimum time problem in view of

Lemma 5. In the absence of $\pi$-singularities, Legendre condition holds.
Proof. If the switching function never vanishes, one has $|u|=1$ everywhere. So we can restrict the control set $U$ to $\mathbf{S}^{1}$. The manifold is without boundary and, in the chart $u=(\cos \alpha, \sin \alpha), \alpha \in \mathbf{R}$, one has $\underbrace{8}$

$$
H(x, \alpha, p)=p^{0}+H_{0}(x, p)+\varepsilon\left(\cos \alpha H_{1}(x, p)+\sin \alpha H_{2}(x, p)\right) .
$$

Accordingly,

$$
\nabla_{u u}^{2} H(x, \alpha, p)=-\varepsilon\left(\cos \alpha H_{1}(x, p)+\sin \alpha H_{2}(x, p)\right)
$$

Along an extremal, $\nabla_{u u}^{2} H(x(t), \alpha(t), p(t))=-\varepsilon|\psi(t)|$ which is bounded over by some negative constant on $\left[0, t_{f}\right]$ as $\psi$ is smooth and nonvanishing.

Using previous knowledge on the two-body minimum time trajectories [14, 13], we are able to compute transfers from a circular orbit around the first primary towards the $L_{2}$ point when $\mu=0$, then to follow the path until any value $\mu \in$ $(0,1)$. The absence of conjugate points - ensuring local optimality - is checked along the path using the hampath code [10, see Fig. 3. A continuation on the target eventually allows to obtain solutions, for instance in the Earth-Moon system ( $\mu \simeq 1.21 e-2$ ) from a geostationary orbit to a circular lunar one for average values of the control magnitude $\varepsilon$, see Fig. 4. To reach lower values of $\varepsilon$, a continuation on this parameter is finally employed as in [13, which emphasizes the role of the topology of the state space previously mentioned. Many local minima exist, yielding as many zeros of the shooting function. When decreasing $\varepsilon$, at some point on the resulting path the number of revolutions around the first primary has to be increased to retain global optimality, which means jumping to another connected component (branch) of the zero set (see Fig. 5). Schematically, the situation is analogous to the one in Riemannian geometry with cut and conjugate points: Up to some point, the path provides minimizers; then global optimality is lost (this is typically a global phenomenon, for instance due to the topology of the manifold), but local optimality persists up to another point; past this second point (a turning point, in the simple case we framed in the beginning of the Section), even local optimality is lost (see Fig. 6).

The computations combining shooting and homotopy presented here are meant to initialize the solution of more complicated problems. A time minimum trajectory of the three-dimensional model of the SMART1 mission [23] is given Fig. 7. Work in progress include the treatment of the maximization of the final mass.
${ }^{8}$ The Hamiltonian lift $H_{0}$ implicitly depends on $\mu$, since $F_{0}=\overrightarrow{J_{\mu}}$ (compare Section 1 .


Figure 3: Conjugate point computation (rotating frame). Extremals (here projected on the $\left(q_{1}, q_{2}\right)$-space) from a circular orbit around the first primary towards the $L_{2}$ Lagrange point are extended beyond the target. Conjugate points, in red, appear after $t_{f}$, ensuring local optimality. Green dots indicate isocost (time) lines.


Figure 4: Minimum time trajectory in the Earth-Moon system ( $\mu \simeq 1.21 e-2$, $\varepsilon=2.44 e-1$ ). Left, in the rotating frame; right, in the fixed frame to emphasize capture by the second primary at the end of the transfer.


Figure 5: Minimum time trajectory for $\varepsilon$ between $2.44 e-1$ and $2.196 e-1$ ( $\mu \simeq 1.21 e-2$, rotating frame). As the control magnitude is decreased, strategies are evolved. In the upper graphs, the first two extremals have the same rotation number around the first primary and both wind around the second one positively. Conversely, the third extremal (bottom left) winds negatively around the second primary, while the fourth (bottom right) makes an additional revolution around the first one.

## Acknowledgements

The authors thank Joseph Gergaud for introducing them to homotopy in optimal control, and Bernard Bonnard for his lasting geometric influence on their work.


Figure 6: Continuation on $\varepsilon$. Down to $\varepsilon_{0}$, branch 1 yields minimizers. In the case of free final time, the shooting unknown is $\xi=\left(t_{f}, p_{0}\right), p_{0}$ belonging to the zero level set of the Hamiltonian. Past $\varepsilon_{0}$, global optimality is lost on branch 1 and a switch to branch 2 has to be made (resulting in a loss of regularity of the value function). Past the turning point on branch 1 (conjugacy of the target point), even local optimality is lost.


Figure 7: Three-dimensional minimum time transfer, SMART1 boundary conditions (fixed frame). The control magnitude $\varepsilon$ is 0.7 Newtons for an initial mass of 350 Kilograms and a specific impulse of 1640 seconds (the variation of mass has been taken into account for this simulation, see [23]). The final time is 26.2 days.

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[^0]:    *Math. Institute, Bourgogne Univ. \& CNRS, 9 avenue Savary, F-21078. Supported by Conseil Régional de Bourgogne (contract no. 2009-160E-160-CE-160T) and ANR Geometric Control Methods (project no. NT09_504490).
    ${ }^{\dagger}$ Same address. Supported by the French Ministry for Higher Education \& Research (grant no. 31716-2008).

[^1]:    ${ }^{1}$ We use $\bar{\partial}=(1 / 2)\left(\partial / \partial q_{1}+i \partial / \partial q_{2}\right)$ to represent the gradient with respect to $q$ in complex form.

[^2]:    ${ }^{2}$ That is $\mathscr{C}{ }^{\infty}$-smooth.

[^3]:    ${ }^{3}$ Given a vector field $F$, a point $x \in X$ is recurrent for $F$ if, for any neighbourhood $V$ of $x$, for any positive $T$, there is $t \geq T$ such that $\exp t F(x)$ is defined and belongs to $V$. The vector field itself is said recurrent when it has a dense subset of recurrent points.

[^4]:    ${ }^{4} \mathrm{~A}$ chart $(O, \varphi)$ in the neighbourhood of $x_{f}$ has to be chosen and the definition should read $p_{0} \mapsto \varphi\left(x\left(t_{f}, x_{0}, p_{0}\right)\right)-\varphi\left(x_{f}\right)$. We may actually suppose that $\varphi\left(x_{f}\right)=0$.
    ${ }^{5}$ This weaker statement is obvious: Were the function a submersion at $\bar{u}$, it would be locally open and would send neighbourhoods of $\bar{u}$ onto neighbourhoods of the augmented state, $\left(\bar{x}^{0}\left(t_{f}\right), \bar{x}\left(t_{f}\right)\right)$. This would contradict $\mathrm{L}^{\infty}$-local optimality.
    ${ }^{6}$ That is optimality on a neighbourhood of $\bar{u}$ in $\mathrm{L}^{\infty}\left(\left[0, t_{f}\right], U\right)$.
    ${ }^{7}$ Optimality of the trajectory among all admissible trajectories belonging to some neighbourhood of $\bar{x}$.

