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ON SINGULARITIES OF MINIMUM TIME CONTROL-AFFINE SYSTEMS*

JEAN-BAPTISTE CAILLAU[†], JACQUES FÉJOZ[‡], MICHAËL ORIEUX[§], AND
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Abstract. Affine control problems arise naturally from controlled mechanical systems. Building on previous results [1, 9] we prove that, in the case of time minimization with control on the disk, the extremal flow given by Pontrjagin’s maximum principle is smooth along the strata of a well-chosen stratification. We also study this flow in terms of regular-singular transition and prove that the singularity along time-minimizing extremals crossing these strata is at most logarithmic. We then apply these results to mechanical systems, paying special attention to the case of the controlled three body problem.

Key words. minimum time, normal hyperbolicity, regular-singular transition, control switching

AMS subject classifications. 49K15, 49N60, 37D20, 70Q05

1. Introduction. The aim of this paper is the study of time minimization for control-affine systems of the form

$$\dot{x}(t) = F_0(x(t)) + u_1(t)F_1(x(t)) + u_2(t)F_2(x(t)), \quad u_1^2(t) + u_2^2(t) \leq 1,$$

where the control $u = (u_1, u_2)$ is thus contained in the disk, and where all vector fields are smooth. For the sake of simplicity, we carry out the reasoning in a 4-dimensional manifold—which is the most relevant for the applications—but the method and results of Section 3 can be adapted to a $2m$ -dimensional manifold with an m -dimensional control. The reason for studying the singularities of such optimal control systems is that the regularity of the Hamiltonian flow given by Pontrjagin’s maximum principle—the *extremal flow*—is crucial to study necessary conditions for optimality, and thus, determine the actual optimal solutions. The numerical study of these problems also strongly depends on regularity. Recently, new genericity results for this kind of singularities have been obtained in [6] for control-affine systems of any dimension with an even number of controls prescribed to the closed unit ball. A similar analysis have been conducted for control constrained in a polyhedron in [19]. (See the beginning of Section 3 for further comments.) Sufficient conditions for optimality have also been proved in [3] for a minimum time control-affine system in a related context.

In the first section, we recall for the sake of completeness some classical results of geometric optimal control, with an emphasis on Pontrjagin maximum principle, which is key to our study and reduces the problem to the study of a singular Hamiltonian system. The singularities of this system are related to the discontinuities of the optimal control u , often called *switches*. We study the local structure of the Hamiltonian flow under generic assumptions in Section 3. The beginning of our study builds upon the analysis in [9] and goes one step further than the recent paper [1] where the flow is proved to be well-defined and continuous (see also [2] in higher dimensions): using

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the underlying normal hyperbolicity of the system, we provide a stratification whose strata carry a smooth flow; the extremal flow is thus piecewise smooth, and continuous. This regular behavior is obtained as a consequence of a straightening normal form lemma, around the singular locus, proved at the end of the section. In Section 4, we investigate the kind of singularity of the flow encountered when crossing strata. Thanks to a suitable normal form, we prove that the associated regular-singular transition results into a logarithmic term, implying that the flow belongs to the log – exp category [24]. This behaviour of the flow strongly contrasts with the situation studied in [11] where singularities of the flow were stable; here, singularities are destroyed by small perturbations of the initial conditions, unless these perturbations belong to a codimension one stratum. We then apply these results to the controlled circular restricted three body problem, in Section 5. We finally investigate global properties of the flow and give upper bounds on the number of switches of the control for this particular nonlinear system. Note that such bounds for time minimization are given in the linear case in [5]. In contrast to [10], where a subset of the switching set was studied, we treat here the general case using a comparison principle.

2. Setting. Let M be a smooth (that is \mathcal{C}^∞ -smooth) 4-dimensional manifold, and let us consider the following control-affine system:

$$(2.1) \quad \dot{x}(t) = F_0(x(t)) + u_1(t)F_1(x(t)) + u_2(t)F_2(x(t)), \quad |u(t)| = \sqrt{u_1^2(t) + u_2^2(t)} \leq 1.$$

Given endpoint conditions $x(0) = x_0$, $x(t_f) = x_f$, one can consider the minimization of the final time, t_f . The corresponding Hamiltonian writes

$$H(x, p, u) = H_0 + u_1 H_1 + u_2 H_2, \quad H_i := \langle p, F_i(x) \rangle, \quad i = 0, 1, 2,$$

and the classical Pontrjagin maximum principle [4] provides a necessary condition for optimality, allowing us to work with a true—that is independent of the control—Hamiltonian system, yet at the expense of introducing singularities.

THEOREM 2.1 (Pontrjagin maximum principle). *Let $u : [0, t_f] \rightarrow \mathbf{R}^2$ be an essentially bounded time minimizing control of (2.1), and let x be the associated trajectory. There exists a Lipschitz curve $p(t) \in T_{x(t)}^*M$ such that, almost everywhere on $[0, t_f]$,*

$$(2.2) \quad \dot{x}(t) = \frac{\partial H}{\partial p}(x(t), p(t), u(t)), \quad \dot{p}(t) = -\frac{\partial H}{\partial x}(x(t), p(t), u(t)),$$

68

$$(2.3) \quad H(x(t), p(t), u(t)) = \max_{|v| \leq 1} H(x(t), p(t), v),$$

and $H(x(t), p(t), u(t)) \geq 0$. Moreover, p does not vanish on $[0, t_f]$.

Triples (x, p, u) solutions of (2.2)-(2.3) are called *extremals*, and their projections on M *extremal trajectories*. We denote by $z = (x, p)$ elements of the cotangent bundle T^*M , where p belongs to the fiber T_x^*M . We define the *switching surface*,

$$\Sigma := \{z = (x, p) \in T^*M \mid H_1(z) = H_2(z) = 0\}.$$

Extremals along which H_1 and H_2 do not vanish simultaneously are called *bang arcs*. An extremal is said to be *bang-bang* if it is a concatenation of bang arcs. The following proposition is clear.

78 PROPOSITION 2.2. *An extremal lying out of Σ is an integral curve of the maxi-*
 79 *mized Hamiltonian*

$$80 \quad H_0(z) + \sqrt{H_1^2(z) + H_2^2(z)}.$$

81 *The associated control belongs to \mathbf{S}^1 and is equal to*

$$82 \quad (2.4) \quad u = \frac{1}{\sqrt{H_1^2 + H_2^2}}(H_1, H_2).$$

83 Let now $\bar{z} = (\bar{x}, \bar{p})$ belong to Σ . We are interested in the local behavior of the extremal
 84 flow in a neighbourhood of this singular point. We make the following transversality
 85 assumption (remember that the ambient manifold is 4-dimensional):

$$86 \quad (\text{A}) \quad \text{Span}_{\bar{x}}\{F_1, F_2, F_{01}, F_{02}\} = T_{\bar{x}}M,$$

87 where $F_{ij} := [F_i, F_j]$ denotes the Lie bracket of vector fields. As a derivation on
 88 functions, $[F_i, F_j]$ is the commutator $F_i F_j - F_j F_i$, while in coordinates $[F_i, F_j](x) =$
 89 $F_j'(x)F_i(x) - F_i'(x)F_j(x)$. Property (A) is generic among vector fields and points of
 90 Σ , and holds in particular for control systems arising from mechanical systems (see
 91 Section 5). Since the adjoint vector cannot be zero, assumption (A) implies that, for
 92 z in a neighbourhood of \bar{z} ,

$$93 \quad H_1^2(z) + H_2^2(z) + H_{01}^2(z) + H_{02}^2(z) \neq 0,$$

94 where $H_{ij} := \{H_i, H_j\}$ now denotes the Poisson bracket of functions on the cotangent
 95 bundle. In accordance with the definition of Lie brackets, in coordinates

$$96 \quad \{H_i, H_j\} = \sum_{k=1}^n \frac{\partial H_i}{\partial p_k} \frac{\partial H_j}{\partial x_k} - \frac{\partial H_i}{\partial x_k} \frac{\partial H_j}{\partial p_k}.$$

97 **3. Stratification of the extremal flow.** Following [9], we partition Σ accord-
 98 ing to

$$99 \quad \Sigma_- := \{z \in \Sigma \mid H_{12}^2(z) < H_{02}^2(z) + H_{01}^2(z)\},$$

$$100 \quad \Sigma_+ := \{z \in \Sigma \mid H_{12}^2(z) > H_{02}^2(z) + H_{01}^2(z)\},$$

$$101 \quad \Sigma_0 := \{z \in \Sigma \mid H_{12}^2(z) = H_{02}^2(z) + H_{01}^2(z)\}.$$

103 In this paper, we focus on the case Σ_- which is the relevant one for mechanical
 104 systems, as explained Section 5. The other situations (in particular Σ_0) will be tackled
 105 in a forthcoming work [17]. The main results of this section refine the analysis in [1]
 106 by using normal hyperbolicity of the system to provide a suitable stratification under
 107 our standing assumption (A).

108 PROPOSITION 3.1. *Let \bar{z} belong to Σ_- ; there exists a neighbourhood $O_{\bar{z}}$ of \bar{z} in*
 109 *T^*M such that (i) for every $z \in O_{\bar{z}}$ there exists a unique extremal passing through z ;*
 110 *(ii) every such extremal intersects Σ at most once in $O_{\bar{z}}$.*

111 *Remark 3.2.* In the terminology of [6], Σ_- points along the extremal are called
 112 *Fuller times of order zero*. In that paper, *Fuller times of higher order* are defined
 113 inductively, and it is shown that, generically, there are only finite order Fuller times.
 114 An upper bound on the order exists that only depends on the dimension of the ambient
 115 manifold. We focus here on the structure of the extremal flow in the neighbourhood of
 116 a single Σ_- point. As we shall see in Section 5, for usual mechanical systems $\Sigma = \Sigma_-$;
 117 this precludes accumulation of switching points (Fuller phenomenon).

118 Let us consider an extremal $z : [0, t_f] \rightarrow T^*M$ as in Proposition 3.1, initializing
119 at $z(0) = \bar{z}_0$ and crossing Σ once at $\bar{z} \in \Sigma_-$ and time $\bar{t} \in (0, t_f)$. The following holds.

120 **THEOREM 3.3.** *There exists an open neighbourhood $O_{\bar{z}_0} \subset T^*M \setminus \Sigma$ of \bar{z}_0 such*
121 *that the extremal flow $(t, z_0) \mapsto z(t, z_0)$ is well defined and continuous on $[0, t_f] \times$*
122 *$O_{\bar{z}_0}$. Moreover, $O_{\bar{z}_0} = S^0 \cup S^s$ where S^s is a codimension one submanifold of initial*
123 *conditions leading to Σ_- , and where $S^0 = O_{\bar{z}_0} \setminus S^s$. The time $t_\Sigma(z_0)$ to reach Σ from*
124 *an initial condition z_0 is well defined and smooth for z_0 in S^s . Both S^0 and S^s*
125 *are stable by the flow which is smooth on $[0, t_f] \times S^0$ and on $([0, t_f] \times S^s) \setminus \Delta$, where*
126 $\Delta = \{(t_\Sigma(z_0), z_0), z_0 \in S^s\}$.

127 *Remark 3.4.* Although the analysis is drawn on a 4-dimensional manifold with
128 control on the 2-disk, it will be clear from the proofs that the same results hold in
129 dimension $2m$ with control on the m -dimensional unit ball. Besides, while we assume
130 that the reference extremal departing at \bar{z}_0 crosses only once Σ for $t \in [0, t_f]$, the
131 analysis can be readily extended to an extremal with a finite number of contacts with
132 Σ at Σ_- points.

133 Let us provide a simple example to illustrate the situation described by Proposition 3.1
134 and Theorem 3.3. Consider the control system

$$135 \quad (3.1) \quad \begin{cases} \dot{x}_1(t) = 1 + x_3(t), & \dot{x}_3(t) = u_1(t), \\ \dot{x}_2(t) = x_4(t), & \dot{x}_4(t) = u_2(t), \end{cases}$$

136 with control in the 2-disk, $u_1^2 + u_2^2 \leq 1$. The maximized Hamiltonian (from Pontrjagin
137 maximum principle) is

$$138 \quad H(x, p) = p_1(1 + x_3) + p_2x_4 + \sqrt{p_3^2 + p_4^2}$$

139 (p_i being the adjoint variable of x_i), and the codimension two submanifold

$$140 \quad \Sigma = \{p_3 = 0\} \cap \{p_4 = 0\} = \Sigma_-$$

141 is the singular locus. (Note that the distribution $\{F_1, F_2\}$ is involutive, so the bracket
142 H_{12} vanishes.) The adjoint states p_1 and p_2 are constant, let $a = -p_1(0)$ and $c =$
143 $-p_2(0)$. We get $p_3(t) = at + b$, $p_4(t) = ct + d$, with $b = p_3(0)$ and $d = p_4(0)$. Then

$$144 \quad (3.2) \quad \dot{x}_3(t) = \frac{at + b}{\sqrt{(at + b)^2 + (ct + d)^2}},$$

145 so that singularities occur when $(at + b, ct + d)$ vanishes for some t , that is when
146 $ad - bc = 0$, which defines the codimension one submanifold $S^s = \{p_1p_4 - p_2p_3 =$
147 $0\} \setminus \{p = 0\}$ (remember that the adjoint state p cannot be zero for a minimum-time
148 extremal by virtue of the maximum principle). We get a symmetric dynamics for x_4
149 and end up with the same submanifold. One verifies that this stratum is stable by
150 the flow of the maximized Hamiltonian. Outside S^s , we can explicitly solve (3.2) and
151 obtain

$$152 \quad x_3(t, z_0) = x_3(0) + \frac{a}{a^2 + c^2} (\sqrt{(at + b)^2 + (ct + d)^2} - \sqrt{b^2 + d^2})$$

$$153 \quad -c \frac{ad - bc}{(a^2 + c^2)^{3/2}} \left[\operatorname{argsh} \left(\frac{(a^2 + c^2)t + ab + cd}{ad - bc} \right) - \operatorname{argsh} \left(\frac{ab + cd}{ad - bc} \right) \right].$$

154 It is clear that the flow is smooth outside S^s . If a and c are zero, p_3 and p_4 become
 155 constant, and since p cannot vanish there are no contacts with Σ . Now observe that
 156 the flow is defined on S^s by

$$157 \quad x_3(t, z_0) = x_3(0) + \frac{a}{a^2 + c^2} (\sqrt{(at + b)^2 + (ct + d)^2} - \sqrt{b^2 + d^2})$$

158 for all $z_0 \in S^s \setminus \{p = 0\}$. Restricted to S^s , the flow is smooth outside switches. We
 159 also have global continuity on T^*M , but not Lipschitz continuity. Furthermore, on
 160 this simple model a singularity of $y \ln y$ type appears when crossing S^s , that is when
 161 the determinant $ad - bc$ goes to zero. We prove in Section 4 that the singularities in
 162 the general case are not worse than in this example.

163 **3.1. Proof of Proposition 3.1.** According to assumption (A), the mapping

$$164 \quad (x, p_1, p_2, p_3, p_4) \mapsto (x, H_1, H_2, H_{01}, H_{02})$$

165 defines a smooth change of coordinates in a small enough neighbourhood $O_{\bar{z}}$ of \bar{z} . A
 166 polar blow-up is used to study the dynamics near the singularity, adding an \mathbf{S}^1 -fiber
 167 above $\rho = 0$:

$$168 \quad (H_1, H_2) = (\rho \cos \theta, \rho \sin \theta), \quad (\rho, \theta) \in \mathbf{R} \times \mathbf{S}^1.$$

169 In polar coordinates, (2.4) reads $u = (\cos \theta, \sin \theta)$, and $\Sigma = \{\rho = 0\}$. Computing, the
 170 dynamics is

$$171 \quad (3.3) \quad X : \begin{cases} x' = \rho(F_0(x) + \cos \theta \cdot F_1(x) + \sin \theta \cdot F_2(x)), \\ \rho' = \rho(\cos \theta \cdot H_{01} + \sin \theta \cdot H_{02}), \\ \theta' = H_{12} + \cos \theta \cdot H_{02} - \sin \theta \cdot H_{01}, \\ H'_{01} = \rho(H_{001} + \cos \theta \cdot H_{101} + \sin \theta \cdot H_{201}), \\ H'_{02} = \rho(H_{002} + \cos \theta \cdot H_{102} + \sin \theta \cdot H_{202}), \end{cases}$$

172 where we have changed time from t to s ($' = d/ds$) with $dt = \rho ds$ to get rid of
 173 the $1/\rho$ singularity on θ , and denoted X the corresponding vector field. In this
 174 new time, the autonomous vector field in the right hand side of (3.3) is smooth,
 175 which implies existence and uniqueness of maximal solutions through a point, as
 176 well as smoothness of the flow. Note that when ρ vanishes, only θ is not constant;
 177 in particular $\Sigma = \{\rho = 0\}$ is invariant by the flow. In the following, we denote
 178 $\bar{H}_{ij} = H_{ij}(\bar{z})$, $i, j = 0, 1, 2$. The next lemma establishes that in each part of Σ , the
 179 derivative of θ has a different number of equilibria.

180 **LEMMA 3.5.** *Let z belong to Σ ; the mapping $\theta \mapsto H_{12} + \cos \theta \cdot H_{02} - \sin \theta \cdot H_{01}$ has*
 181 *(i) two zeros, denoted by θ_- and θ_+ , for z in Σ_- ; (ii) exactly one zero for z in Σ_0 ; (iii)*
 182 *no zero for z in Σ_+ . In the $z \in \Sigma_-$ case, the two mappings $(x, H_{01}, H_{02}) \mapsto \theta_{\pm}$*
 183 *are well defined and smooth in a neighbourhood of $(\bar{x}, \bar{H}_{01}, \bar{H}_{02})$.*

184 *Proof.* Setting $(H_{01}, H_{02}) = (r \cos \phi, r \sin \phi)$ where $r \neq 0$ under assumption (A),

$$185 \quad H_{12} + \cos \theta \cdot H_{02} - \sin \theta \cdot H_{01} = H_{12} - r \sin(\theta - \phi),$$

186 so $H_{12}/r = \sin(\theta - \phi)$ has two solutions, θ_- and θ_+ , if $\bar{z} \in \Sigma_-$, no solution if $z \in \Sigma_+$
 187 and exactly one if $z \in \Sigma_0$ (since $H_{12}(z)/r = \pm 1$). The variables $(x, \theta, H_{01}, H_{02})$ define
 188 a local chart on $\Sigma = \{\rho = 0\}$, and the mapping

$$189 \quad g : (x, \theta, H_{01}, H_{02}) \mapsto H_{12} + \cos \theta \cdot H_{02} - \sin \theta \cdot H_{01}$$

190 verifies

$$191 \quad \frac{\partial g}{\partial \theta}(x, \theta_{\pm}, H_{01}, H_{02}) = -r \cos(\theta_{\pm} - \phi) = \pm \sqrt{r^2 - H_{12}^2} \neq 0,$$

192 so the implicit function theorem allows to conclude. \square

193 To complete the proof of Proposition 3.1, let us recall that a diffeomorphism f of
 194 manifold M onto itself is said to be normally hyperbolic along a compact submanifold
 195 N if the submanifold N is invariant by f and if (i) every fibre of the tangent bundle
 196 of M along N admits a splitting $T_x M = E^u(x) \oplus T_x N \oplus E^s(x)$ for all $x \in N$ such that
 197 $f'(x) \cdot E^s(x) = E^s(f(x))$ and $f'(x) \cdot E^u(x) = E^u(f(x))$ (f preserves the splitting);
 198 (ii) there exists $\lambda_1 \leq \mu_1 < \lambda_2 \leq \mu_2 < \lambda_3 \leq \mu_3$, with $\mu_1 < 1 < \lambda_3$, such that (the
 199 endomorphism norm below being induced by a given Riemannian structure on M)

$$200 \quad (3.4) \quad \lambda_1 \leq |f'|_{E^s} \leq \mu_1, \quad \lambda_2 \leq |f'|_{TN} \leq \mu_2, \quad \lambda_3 \leq |f'|_{E^u} \leq \mu_3.$$

201

202 The distributions E^s and E^u are locally integrable, and one can construct the local
 203 stable and unstable manifolds, $W(x)^s$ and $W(x)^u$, respectively tangent to $E^s(x)$ and
 204 $E^u(x)$ at each point $x \in N$. One also defines $\mathcal{W}^s := \bigcup_{x \in N} W^s(x)$ and $\mathcal{W}^u :=$
 205 $\bigcup_{x \in N} W^u(x)$, the local stable and unstable manifolds of N . Let also l_s and l_u be
 206 the biggest integers such that $\mu_1 \leq \lambda_2^{l_u}$ and $\mu_2^{l_s} \leq \lambda_3$. The following holds (see
 207 (Theorem 3.5 in [14], or [18]), giving the regularity of the stable and unstable manifolds
 208 in terms of the ratio of the contraction and expansion rates.

209 **THEOREM 3.6** (Hirsch, Pugh, Shub). *Any f -invariant submanifold which is close*
 210 *enough to N is included in $\mathcal{W}^s \cup \mathcal{W}^u$. Furthermore, \mathcal{W}^s and \mathcal{W}^u are submanifolds of*
 211 *class \mathcal{C}^{l_s} and \mathcal{C}^{l_u} , respectively.*

212 In our case, this result is applied on the cotangent bundle T^*M of the original state
 213 manifold M , and we have two codimension two submanifolds of equilibrium points,
 214 namely

$$215 \quad z_{\pm} = (x, \rho = 0, \theta = \theta_{\pm}(x, H_{01}, H_{02}), H_{01}, H_{02}),$$

216 parameterized locally by $y := (x, H_{01}, H_{02})$ in a neighbourhood of $(\bar{x}, \bar{H}_{01}, \bar{H}_{02})$. We
 217 set

$$218 \quad (3.5) \quad \cos \theta_- \cdot H_{01} + \sin \theta_- \cdot H_{02} = -\sqrt{r^2 - H_{12}^2} < 0,$$

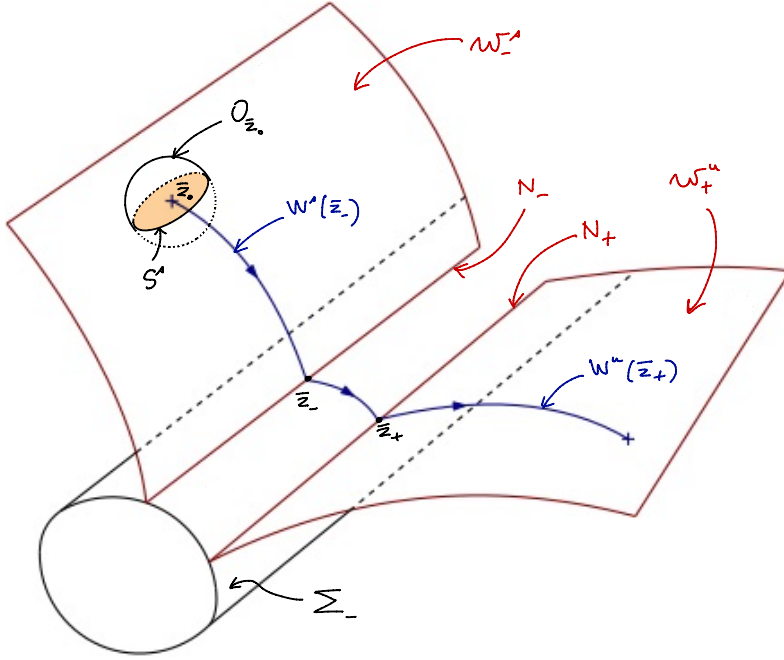
219 and the opposite for θ_+ . The Jacobian of the system (3.3) has two non-zero eigenvalues
 220 at those points: $\cos \theta_{\pm} \cdot H_{01} + \sin \theta_{\pm} \cdot H_{02}$ and their opposite, and a 6-dimensional kernel.
 221 So we have a one-dimensional stable submanifold $W^s(z_{\pm})$, and a one-dimensional
 222 unstable submanifold $W^u(z_{\pm})$ in every equilibrium z_{\pm} . The flow is thus normally
 223 hyperbolic to the manifold

$$224 \quad N_- = \{z = z_-(y) = (\rho = 0, \theta = \theta_-(y), y)\},$$

225 and symmetrically to

$$226 \quad N_+ = \{z = z_+(y) = (\rho = 0, \theta = \theta_+(y), y)\}.$$

227 We now focus on the case of N_- , the analysis being the same for N_+ . On N_-
 228 the dynamics is trivial: every point is an equilibrium. Hence there exists a unique
 229 trajectory converging to z_- when $s \rightarrow \infty$ in the stable manifold $W^s(z_-)$. On Σ ,


 FIG. 1. Switching set Σ_- and extremal flow after blow-up, and stratification.

230 everything is constant but θ , which realizes a heteroclinic connection from θ_- to θ_+ .
 231 Symmetrically, there is one trajectory converging to z_+ when $s \rightarrow -\infty$ in the unstable
 232 manifold $W^u(z_+)$. Blowing down from (ρ, θ) to (H_1, H_2) , there is a unique extremal
 233 passing through every $z \in \Sigma$ in a small enough neighbourhood $O_{\bar{z}}$ of \bar{z} , and those
 234 extremals cross Σ only once if the neighbourhood is small enough. Furthermore, in
 235 the original time t , this happens in finite time for any initial conditions in $O_{\bar{z}}$ leading
 236 to the singular locus. Indeed, note that the negative expression in (3.5) is smooth and
 237 bounded on $O_{\bar{z}}$. Let $C < 0$ be a negative upper bound; given the dynamics of ρ , one
 238 has $\rho'(s) \leq \rho(s)C$, and $\rho(s) \leq \rho(0)e^{Cs}$ by Gronwall's Lemma. So the time t required
 239 to reach Σ is bounded by

$$\int_0^\infty \rho(s) ds \leq -\frac{\rho(0)}{C} < \infty.$$

241 All in all, through every z in $O_{\bar{z}}$ passes a unique extremal either crossing Σ exactly
 242 once, or not crossing Σ at all. This concludes the proof of Proposition 3.1.

243 **3.2. Proof of Theorem 3.3.** Let $z : [0, t_f] \rightarrow T^*M$ be an extremal departing
 244 from some \bar{z}_0 and crossing Σ at $\bar{z} \in \Sigma_-$ and $\bar{t} \in (0, t_f)$. According to what we have
 245 proved in the previous subsection, (2.2)-(2.3) admits a unique solution defined on
 246 $[0, t_f]$ for an initial condition z_0 close enough to \bar{z}_0 . So there exists a small enough
 247 open neighbourhood $O_{\bar{z}_0}$ of \bar{z}_0 such that the flow $z(t, z_0)$ of (2.2)-(2.3) is well defined
 248 for $(t, z_0) \in [0, t_f] \times O_{\bar{z}_0}$. In particular, $z(t, \bar{z}_0) = z(t)$, the reference extremal. We
 249 use the normally hyperbolic invariant manifold N_- previously constructed to define
 250 $\mathcal{W}_-^s := \bigcup_{z \in N_-} W^s(z)$. Since N_- is made of equilibria, $\lambda_2 = \mu_2 = 1$ in the splitting
 251 (3.1) at any point of N_- , and \mathcal{W}_-^s is a \mathcal{C}^∞ -smooth submanifold whose dimension is

252 $7 = \dim N + 1$, every fiber $W^s(z)$ being of dimension one. The stratum we look for is

$$253 \quad S^s := \mathcal{W}_-^s \cap \{\rho > 0\}.$$

254 One can similarly define $\mathcal{W}_+^u := \bigcup_{z \in N_+} W^u(z)$, also \mathcal{C}^∞ -smooth of codimension one,
255 and $S^u := \mathcal{W}_+^u \cap \{\rho > 0\}$.

256 To understand the regularity of the flow on this strata, we use a normal form to
257 rewrite the system in the neighbourhood of the equilibria θ_- . (The same approach
258 also works near θ_+ .) Using again polar coordinates $(H_{01}, H_{02}) = (r \cos \phi, r \sin \phi)$, the
259 dynamics (3.3) writes

$$260 \quad (3.6) \quad \begin{cases} \rho' = r\rho \cos(\theta - \phi), \\ \theta' = H_{12} - r \sin(\theta - \phi), \\ \xi' = \rho h(\rho, \theta, \xi), \end{cases}$$

261 where $\xi = (x, r, \phi)$ and h is a smooth function. We set $\psi = \theta - \phi$, rescale the time
262 according to $dv = r ds$ (as (A) implies $r > 0$ in the neighbourhood of \bar{z}), and study a
263 system with the following structure (the derivation wrt. v still being noted $'$):

$$264 \quad (3.7) \quad \begin{cases} \rho' = \rho \cos \psi, \\ \psi' = g(\rho, \psi, \xi) - \sin \psi =: G(\rho, \psi, \xi), \\ \xi' = \rho h(\rho, \psi, \xi), \end{cases}$$

265 where g is a smooth function (so is G) defined on an open set O of $\mathbf{R}^2 \times D$, D being
266 a compact domain of \mathbf{R}^6 . As H_{12} is a smooth function in $(H_1, H_2) = (\rho \cos \theta, \rho \sin \theta)$,
267 because it is smooth wrt. the change of coordinates given by assumption (A),

$$268 \quad g(\rho, \psi, \xi) = a(\xi) + \rho b(\xi, \psi) + O(\rho^2)$$

269 since when $\rho = 0$, g does not depend anymore on θ . Besides, $|g| < 1$ on O since it
270 is a small neighbourhood of Σ_- . Equilibria occur when $\rho = G = 0$. They are semi-
271 hyperbolic, since they are outside $\{\psi = \pm\pi/2\}$ for \bar{z} in Σ_- . More precisely, it was
272 shown in the previous subsection that the flow of this system is normally hyperbolic
273 to the manifold $\{\rho = 0\} \cap \{G = 0\}$. For each ξ , we retrieve the two equilibria z_\pm ,
274 and the previously defined θ_\pm are mapped to ψ_\pm in the new set of coordinates for the
275 blow-up. Indeed, thanks to the structure of g , we get $\partial g / \partial \psi(0, \psi, \xi) = 0$, so

$$276 \quad \frac{\partial G}{\partial \psi}(0, \psi, \xi) = -\cos \psi \neq 0,$$

277 and there exist two smooth functions $\psi_\pm(\xi)$ that allow to parameterize anew the two
278 pieces of $\{G = 0\} \cap \{\rho = 0\}$ according to

$$279 \quad N_\pm = \{z = z_\pm(\xi) = (\rho = 0, \psi = \psi_\pm(\xi), \xi)\}.$$

280 The following result is a preparation lemma for the normal form computation.

281 **LEMMA 3.7.** *In a neighbourhood of N_- , the vector field X giving system (3.3) is*
282 *smoothly conjugated to a vector field Y (that is there exists a smooth diffeomorphism*
283 *Ψ s.t. $\Psi_* X = Y$) such that*

$$284 \quad (3.8) \quad Y : \begin{cases} \rho' = -\rho(1 + O(|\rho| + |\omega|)), \\ \omega' = \omega + O((|\rho| + |\omega|)^2), \\ \xi' = \rho O(|\rho| + |\omega|), \end{cases}$$

285 *in suitable coordinates (ρ, ω, ξ) .*

286 *Proof.* Let us set $\omega = \psi - \psi_-(\xi)$ along $\{G = 0\}$, and study the system near $\omega = 0$.
 287 In these new coordinates,

$$288 \quad \begin{cases} \rho' = \rho \cos(\omega + \psi_-(\xi)), \\ \omega' = g(\rho, \omega + \psi_-(\xi), \xi) - \sin(\omega + \psi_-(\xi)) - \rho \frac{\partial \psi}{\partial \xi}(\xi) \cdot h(\rho, \omega + \psi_-(\xi), \xi), \\ \xi' = \rho h(\rho, \omega + \psi_-(\xi), \xi). \end{cases}$$

289 Then

$$290 \quad g(\rho, \omega + \psi_-(\xi), \xi) = a(\xi) + \rho b(\omega + \psi_-(\xi), \xi) + O(\rho^2),$$

291 so $g(0, \psi_-(\xi), \xi) = \sin(\psi_-(\xi)) = a(\xi)$. So (3.3) is equivalent to

$$292 \quad (3.9) \quad \begin{cases} \rho' = \lambda(\xi)\rho(1 + O(|\rho| + |\omega|)), \\ \omega' = \beta(\xi)\rho - \lambda(\xi)\omega + O((|\rho| + |\omega|)^2), \\ \xi' = \rho(\gamma(\xi) + O(|\rho| + |\omega|)), \end{cases}$$

293 with $\lambda(\xi) = \cos(\psi_-(\xi))$ and β, γ smooth functions. The Jacobian matrix of the right
 294 hand side in (3.9) is

$$295 \quad \begin{pmatrix} \lambda(\xi) & 0 & 0 \\ \beta(\xi) & -\lambda(\xi) & 0 \\ \gamma(\xi) & 0 & 0 \end{pmatrix}.$$

296 Let us change coordinates further in order to diagonalize this Jacobian. Consider
 297 $\tilde{\omega} = \omega + g_1(\xi)\rho$ and $\tilde{\xi} = \xi + g_2(\xi)\rho$, with g_1 and g_2 to be chosen. One has

$$298 \quad \tilde{\omega}' = \omega' + \frac{\partial g_1}{\partial \xi}(\xi)\xi'\rho + g_1(\xi)\rho',$$

299 so $\tilde{\omega}' = (\beta(\xi) + 2g_1(\xi)\lambda(\xi))\rho - \lambda(\xi)\tilde{\omega} + O((|\rho| + |\omega|)^2)$, and by picking $g_1 = -\beta/(2\lambda)$
 300 we obtain what we look for. Indeed, with this change of variables, $O((|\rho| + |\omega|)^k) =$
 301 $O((|\rho| + |\tilde{\omega}|)^k)$ for all k ; moreover

$$302 \quad \tilde{\xi}' = \xi' + \frac{\partial g_2}{\partial \xi}(\xi)\xi'\rho + g_2(\xi)\rho' = \rho(\gamma(\xi) + g_2(\xi)\lambda(\xi)) + O((|\rho| + |\omega|)^2),$$

303 and we choose $g_2 = -\gamma/\lambda$. In these new variables,

$$304 \quad \begin{cases} \rho' = \lambda(\tilde{\xi})\rho(1 + O(|\rho| + |\tilde{\omega}|)), \\ \tilde{\omega}' = -\lambda(\tilde{\xi})\tilde{\omega} + O((|\rho| + |\tilde{\omega}|)^2), \\ \tilde{\xi}' = \rho O(|\rho| + |\tilde{\omega}|). \end{cases}$$

305 A smooth change of time finishes the proof. \square

306 **PROPOSITION 3.8** (\mathcal{C}^∞ -normal form). *Set $\Omega = \rho\omega$; there exist A, B, C smooth*
 307 *functions on a neighbourhood of $\{0\} \times D$ such that the vector field Y in (3.8) is*
 308 *smoothly conjugated to*

$$309 \quad (3.10) \quad Y^\infty : \begin{cases} \rho' = -\rho(1 + \Omega A(\Omega, \xi)), \\ \omega' = \omega(1 + \Omega B(\Omega, \xi)), \\ \xi' = \Omega C(\Omega, \xi). \end{cases}$$

310 We postpone the proof of Proposition 3.8 to the end of the section and proceed to
 311 prove Theorem 3.3.

312 LEMMA 3.9. *For z_0 in S^s , the contact point $z_\Sigma(z_0)$ and the contact time $t_\Sigma(z_0)$*
 313 *with Σ are well defined. These two mappings are smooth functions of z_0 on S^s .*

314 *Proof.* Thanks to Proposition 3.8, the globally invariant manifold S^s , fibered by
 315 stable manifolds, is straightened to $\{\omega = 0, \rho \geq 0\}$. But on $\{\omega = 0\}$, we have the
 316 trivial dynamics

$$317 \quad \begin{cases} \rho' = -\rho, \\ \omega' = 0, \\ \xi' = 0. \end{cases}$$

318 In particular, associating to an initial condition $z_0 = (\rho_0, 0, \xi_0)$ on the stable stratum
 319 the contact point with Σ is simply projecting to $(0, 0, \xi_0)$, so the mapping $z_0 \mapsto z_\Sigma(z_0)$
 320 is smooth on S^s . Moreover, $\rho(v) = e^{-v}\rho_0$, where v is the new time $dt = \rho dv / (r\lambda(\xi))$
 321 (see the proof of Proposition 3.8). As a result,

$$322 \quad t_\Sigma(z_0) = \int_0^\infty \frac{\rho(v)}{r(\xi(v))\lambda(\xi(v))} dv = \frac{\rho_0}{r(\xi_0)\lambda(\xi_0)}$$

323 which is also smooth on S^s . □

324 Let $t \in [0, t_f]$, and let z_0 be close enough to the initial condition \bar{z}_0 of the reference
 325 extremal. If z_0 does not belong to S^s , the extremal curve $z(t, z_0)$ does not meet Σ
 326 and is well defined. If (t, z_0) belongs to $([0, t_f] \times S^s) \setminus \Delta$, either $t < t_\Sigma(z_0)$ and $z(t, z_0)$
 327 is again the value at t of the smooth extremal curve, or $t > t_\Sigma(z_0)$ and our analysis
 328 shows that $z(t, z_0)$ is uniquely defined and such that

$$329 \quad z(t, z_0) = z(t - t_\Sigma(z_0), z_\Sigma(z_0)).$$

330 It is clear that this construction leads to a flow which is smooth on $[0, t_f] \times S^0$, and
 331 also on $([0, t_f] \times S^s) \setminus \Delta$ thanks to Lemma 3.9. To conclude the proof of Theorem 3.3,
 332 it remains to prove that the flow is continuous on $O_{\bar{z}_0}$.

333 Let z_0 and z_1 belong to $O_{\bar{z}_0}$, with $z_0 \in S^s$, two close times t_0, t_1 in $[0, t_f]$, and O_δ
 334 be a small neighbourhood of $\bar{z} := z_\Sigma(\bar{z}_0)$. The extremal from z_0 is passing through
 335 $z_\Sigma(z_0) \in O_\delta$. We want to control the quantity $|z(t_1, z_1) - z(t_0, z_0)|$. Suppose, without
 336 loss of generality, that $t_0, t_1 > t_\Sigma(z_0)$. Let $\varepsilon > 0$, and denote t_δ the contact time with
 337 O_δ of the extremal starting from z_0 , *resp.* t'_δ the exit time from this neighbourhood.
 338 We can choose z_0 and z_1 to be close enough, so that $|z(t_\delta, z_0) - z(t_\delta, z_1)| < \varepsilon/3$; simply
 339 because the flow is continuous when the singular locus is not crossed yet. We will
 340 use the following Lemma which gives a uniform bound on the time interval spent by
 341 extremals in a neighbourhood of \bar{z} to conclude (the result appears in [1], we give an
 342 alternative proof):

343 LEMMA 3.10 ([1]). *For all $\delta > 0$ there exists a neighbourhood O_δ of \bar{z} in which*
 344 *every extremal spends a time smaller than δ .*

345 *Proof.* We will prove it in a neighbourhood of \bar{z}_- , the situation being symmetric
 346 around \bar{z}_+ . Let us define $O_{\delta-} = \{z \mid \rho < \delta, |\theta - \theta_-| < \delta\}$, on which $z \mapsto \cos \theta \cdot$
 347 $H_{01}(z) + \sin \theta \cdot H_{02}(z)$ is smooth and thus bounded. Now set

$$348 \quad M_\delta = \sup_{z \in O_{\delta-}} \cos \theta \cdot H_{01}(z) + \sin \theta \cdot H_{02}(z),$$

349 and remember it is negative on $O_{\delta-}$. Then, for any extremal in $O_{\delta-}$, $\dot{\rho}(s) \leq M_\delta \rho(s)$,
 350 which implies

$$351 \quad \rho(s) \leq \rho(0)e^{M_\delta s}.$$

352 So we bound the time spent in $O_{\delta-}$ by

$$353 \quad \Delta_{O_{\delta-}} t \leq \int_0^\infty \rho(0) e^{M_\delta s} ds = -\frac{\delta}{M_\delta}.$$

354 As M_δ tends to a negative value when δ tends to zero, this quantity tends to 0 when δ
 355 does, so every extremal spends an arbitrarily small time in that set. The same holds
 356 for the time interval $\Delta_{O_{\delta+}} t$ in a similarly defined neighbourhood of \bar{z}_+ , say $O_{\delta+}$. This
 357 settles the case of extremals going through the singular locus. Let z be an extremal
 358 without singularity. The time interval in a neighbourhood O_δ can be expressed as
 359 follows:

$$360 \quad \Delta_{O_\delta} t = \Delta_{O_{\delta-}} t + \int_{s_-}^{s_+} \rho ds + \Delta_{O_{\delta+}} t,$$

361 as z exits $O_{\delta-}$ at time s_- and enters $O_{\delta+}$ at time s_+ (see Figure 2). To tackle the
 362 central part of this sum, let us go back to system (3.10).

$$363 \quad Y^\infty : \begin{cases} \rho' = -\rho(1 + \Omega A(\Omega, \xi)), \\ \omega' = \omega(1 + B(\Omega, \xi)), \\ \xi' = \Omega C(\Omega, \xi), \end{cases}$$

364 which, by a time rescaling, is equivalent to

$$365 \quad Y^\infty : \begin{cases} \rho' = -\rho(1 + \Omega \tilde{A}(\Omega, \xi)), \\ \omega' = \omega, \\ \xi' = \Omega \tilde{C}(\Omega, \xi), \end{cases}$$

366 with \tilde{A} standing for $(A - B)/(1 + \Omega B)$, and \tilde{C} for $C/(1 + \Omega B)$. Because of the change
 367 of coordinates $\tilde{\omega} = \omega + g_1(\xi)\rho$, when $s = s_-$ one has $\tilde{\omega}_\pm := \tilde{\omega}(s_\pm) = \delta + g_1(\xi_\pm)\rho(s_\pm)$.
 368 Let us denote s_2 the new time, with $ds_2 = ds/(r\lambda(1 + \Omega B))$. The denominator is
 369 bounded below by a positive constant in O_δ , so $s_+ - s_- \leq M(s_{2+} - s_{2-})$. We also
 370 have $s_{2+} - s_{2-} = \ln(\tilde{\omega}_+/\tilde{\omega}_-)$. So

$$371 \quad \int_{s_-}^{s_+} \rho ds \leq M\delta \ln \left(\frac{\delta + g_1(\xi_+)\rho_+}{\delta + g_1(\xi_-)\rho_-} \right)$$

372 which tends to 0 whenever δ does. This concludes the proof of the lemma. \square

373 Then, with a good choice of O_δ , $|z(t'_\delta, z_0) - z(t_\delta, z_0)|$ and $|z(t'_\delta, z_1) - z(t_\delta, z_1)|$ are
 374 smaller than $\varepsilon/3$, so that $|z(t'_\delta, z_0) - z(t'_\delta, z_1)| \leq |z(t'_\delta, z_0) - z(t_\delta, z_0)| + |z(t_\delta, z_0) -$
 375 $z(t_\delta, z_1)| + |z(t_\delta, z_1) - z(t'_\delta, z_1)| \leq \varepsilon$. Now notice that $z(t_0, z_0) = z(t_0 - t'_\delta, z(t'_\delta, z_0))$,
 376 and use the regularity of the system when the singular locus is not crossed to conclude
 377 the proof of Theorem 3.3.

378 *Remark 3.11.* In the case $\bar{z} \in \Sigma_-$, we can compute the jump on the control at
 379 the switching time \bar{t} in terms of Poisson brackets:

$$380 \quad (3.11) \quad u(\bar{t}_+) - u(\bar{t}_-) = \frac{2\sqrt{r^2(\bar{z}) - \bar{H}_{12}^2}}{r^2(\bar{z})} (\bar{H}_{01}, \bar{H}_{02}).$$

381 *Proof (of Proposition 3.8).* The argument is based on a generalization of the
 382 Poincaré-Dulac theorem. Denote H^l the space of homogeneous polynomials of de-
 383 gree l in \mathbf{R}^n with smooth coefficients in $\xi \in \mathbf{R}^k$. We recall that for a linear vec-
 384 tor field X that does not depend on ξ (and has no component in the ξ direction),

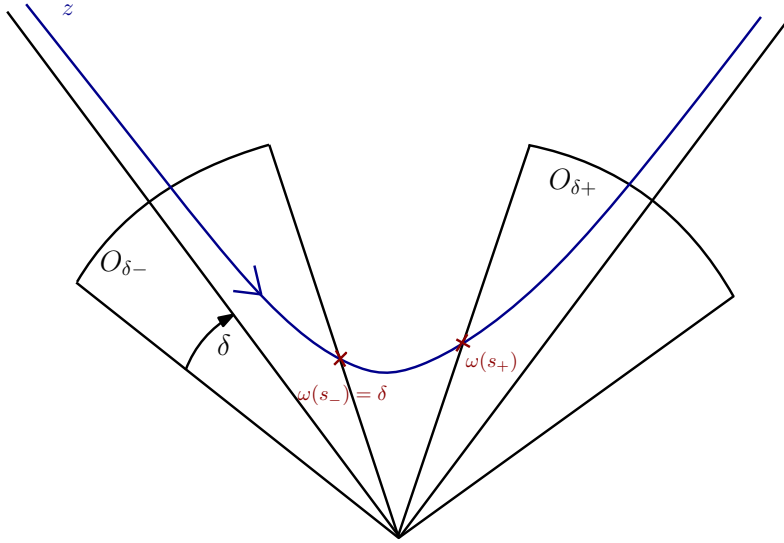


FIG. 2. Extremal entering O_δ with $\theta(s_-) = \theta_- + \delta$, that is $\omega(s_-) = \delta$.

385 $H^l = \text{im}[X, \cdot]_{|H^l} + \ker[X, \cdot]_{|H^l}$. A vector field Z is said to be resonant with X if
 386 $Z \in \ker[X, \cdot]$

387 LEMMA 3.12. Let $X(x, \xi)$ be a smooth vector field in $\mathbf{R}^n \times \mathbf{R}^k$, $X(0, \xi) = 0$.
 388 Denote by X_1 its linear part. Then, if X_1 does not depend on ξ , there exist $g_i \in$
 389 $H^i \cap \ker[X_1, \cdot]$, $i = 2, \dots, l$, and a smooth vector field R_l with zero l -jet such that, in
 390 a neighbourhood of zero, X is smoothly conjugate to

$$391 \quad X_1 + g_2 + \dots + g_l + R_l, \quad l \in \mathbf{N}.$$

392 *Proof.* We will follow [23] and reason by induction on l , then treat the case $l = \infty$.
 393 For $l = 1$, the result is trivial: $X = X_1 + R_1$ where R_1 has zero first jet at zero. Suppose
 394 by induction that g_1, \dots, g_{l-1} , and R_{l-1} are as desired, $l \geq 2$; R_{l-1} has a zero $l-1$
 395 jet (at zero) and can be written as

$$396 \quad R_{l-1} = [X_1, Z] + g_l + R_l,$$

397 where $Z \in H^l$, $g_l \in \ker[X_1, \cdot]$, and R_l is a smooth vector field with zero l -jet. Now,

$$398 \quad [X, Z] = [X_1, Z] + \sum_{i=2}^l [g_i, Z] + [R_{l-1}, Z] = [X_1, Z] + R'_l,$$

399 where R'_l has zero l -jet. Note ϕ_Z the flow of Z , and consider $X^t := (\phi_Z^t)_* X$. One has

$$400 \quad \frac{dX^t}{dt} = [X, Z] = [X_1, Z] + R'_l,$$

401 so that $X^t = X^0 + t[X_1, Z] + R_{l,t}$ with $j^l(R_{l,t})(0) = 0$. Since Z is a homogeneous
 402 polynomial of degree l , it has zero $l-1$ jet, so X and X^t have the same $l-1$ jet,
 403 which means that

$$404 \quad X^0 = X_1 + g_2 + \dots + g_l + [X_1, Z].$$

405 For $t = -1$, $X^{-1} = X_1 + g_2 + \dots + g_l + R_{l,-1}$, and ϕ_Z^{-1} conjugates the two vector fields,
 406 which ends the proof by induction. The above construction provides a sequence of
 407 formal diffeomorphisms $\varphi_l = \phi_Z^{-1}$ ($Z \in H^l$) such that $(\varphi_l)_*X = X_1 + g_2 + \dots + g_l + R_l$.
 408 Also notice that φ_l and φ_{l+1} have the same l -jet. This defines a sequence of coefficients
 409 $g_l(\xi)$ for all l . \square

410 By a generalization of Borel theorem proved by Malgrange in [15], we know that there
 411 exists a smooth function φ such that the l -jet of φ_l and φ are identical for all $l \in \mathbf{N}$.
 412 We can also realize, using the same theorem, the formal series given by the resonant
 413 monomials by a smooth vector field X^∞ . Thus we have $\varphi_*(X) = X^\infty + R^\infty$, where
 414 R^∞ has zero infinite jet. We begin by looking for monomials that are resonant with
 415 the linearized vector field of Y ,

$$416 \quad Y_1 = -\rho \frac{\partial}{\partial \rho} + \omega \frac{\partial}{\partial \omega}$$

417 (monomials X for which $[Y_1, X] = 0$). The Lie bracket with Y_1 treats ξ as a constant:
 418 the map $X \mapsto [Y_1, X]$ is linear in ξ . There are three different cases for such monomials
 419 and

$$420 \quad [Y_1, a(\xi)\rho^i\omega^j \frac{\partial}{\partial \rho}] = (i - j - 1)a(\xi)\rho^i\omega^j \frac{\partial}{\partial \rho},$$

$$421 \quad [Y_1, b(\xi)\rho^i\omega^j \frac{\partial}{\partial \omega}] = (i + 1 - j)b(\xi)\rho^i\omega^j \frac{\partial}{\partial \omega},$$

$$422 \quad [Y_1, c(\xi)\rho^i\omega^j \frac{\partial}{\partial \xi}] = (i - j)c(\xi)\rho^i\omega^j \frac{\partial}{\partial \xi}.$$

423
 424
 425 Setting $\Omega := \rho\omega$, the monomials we are looking for are

$$426 \quad a(\xi)\rho\Omega^k \frac{\partial}{\partial \rho}, \quad b(\xi)\omega\Omega^k \frac{\partial}{\partial \omega}, \quad c(\xi)\Omega^k \frac{\partial}{\partial \xi}, \quad k \in \mathbf{N}.$$

427 The lemma allows us to state that the infinite jet of Y can be formally developed on
 428 the resonant monomials, so Y is formally conjugate to

$$429 \quad W : \begin{cases} \rho' = -\rho(1 + \sum_{i \geq 1} a_i(\xi)\Omega^i), \\ \omega' = \omega(1 + \sum_{i \geq 1} b_i(\xi)\Omega^i), \\ \xi' = \rho \sum_{i \geq 1} c_i(\xi)\Omega^i. \end{cases}$$

430 Notice that, by putting Ω in factor in the formal series above, we get a formal field
 431 of the required form (3.10). There exists Y^∞ , a smooth vector field on O , such that
 432 $W = Y^\infty + R^\infty$ where R^∞ is a smooth function with zero infinite jet along D . At this
 433 stage, we have that Y is smoothly equivalent to $Y^\infty + R^\infty$. The last step consists in
 434 killing the flat perturbation R^∞ . This can be achieved by the path's method: instead
 435 of looking for a diffeomorphism sending $Y_0 := Y$ on $Y_1 := Y^\infty + R^\infty$, we search for a
 436 one parameter family (path) of diffeomorphism $(g_t)_t$ such that

$$437 \quad (3.12) \quad g_t^* Y_0 = Y_t,$$

438 Y_t being a path of vector fields joining Y_0 and Y_1 . Consider the linear path $Y_t =$
 439 $(1 - t)Y_0 + tY_1$, $t \in [0, 1]$. Differentiating (3.12) with respect to t we get

$$440 \quad (3.13) \quad \frac{\partial}{\partial t}(g_t^* Y_0) = \dot{Y}_t = Y_1 - Y_0 = R^\infty.$$

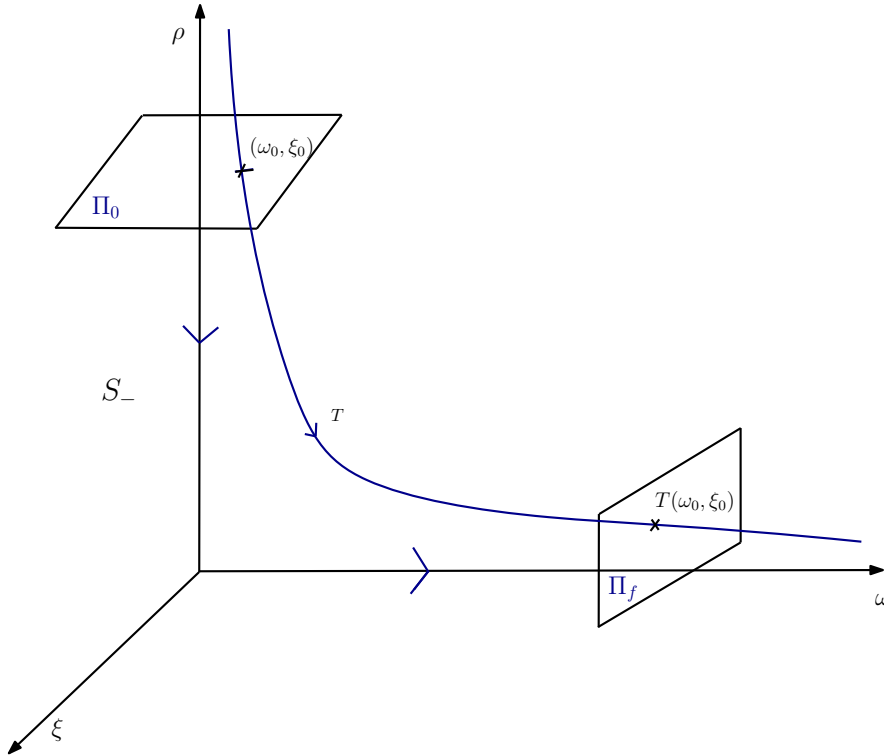


FIG. 3. Transition map between the two sections.

441 The family g_t defines a family of vector fields Z_t by

$$442 \quad Z_t(g_t(x)) = \frac{\partial}{\partial t} g_t(x),$$

443 and conversely we obtain the desired path of diffeomorphisms by integrating these
444 fields. As a consequence, (3.13) can be rewritten

$$445 \quad (3.14) \quad [Y_t, Z_t] = R^\infty.$$

446 We just showed that getting rid of the flat perturbation R^∞ boils down to finding a
447 solution to (3.14). It has been proved in [21] (see Theorem 10), that this equation has
448 a solution. This ends the proof of Proposition 3.8. \square

449 **4. Regular-singular transition.** The existence of a stratification of the flow
450 in the Σ_- case raises the question of the transition: how does the flow behave when
451 one is getting close to the stratum S^s ? We answer this question by considering the
452 Poincaré map between two well chosen sections. Using the normal form given by
453 Proposition 3.8, it is possible to make a precise statement: for given ρ_0 and ω_f , both
454 positive, consider the two sections $\Pi_0 \subset \{\rho = \rho_0\}$ and $\Pi_f \subset \{\omega = \omega_f\}$. As Π_0 is
455 transverse to $\{\omega = 0\}$, it can be parameterized by (ω, ξ) coordinates. Similarly, Π_f is
456 transverse to $\{\rho = 0\}$ and can be parameterized by (ρ, ξ) coordinates (see Figure 3).

457 **THEOREM 4.1.** *Let $T : \Pi_0 \rightarrow \Pi_f$ be the Poincaré mapping between the two sec-*
458 *tions, $T(\omega_0, \xi_0) = (\rho(\omega_0, \xi_0), \xi(\omega_0, \xi_0))$. There exist smooth functions P and X defined*

459 on a neighbourhood of $\{(0, 0)\} \times D$ such that

$$460 \quad T(\omega_0, \xi_0) = (P(\omega_0 \ln \omega_0, \omega_0, \xi_0), X(\omega_0 \ln \omega_0, \omega_0, \xi_0)).$$

461 *Remark 4.2.* The mapping T belongs to the log-exp category [24]. (See [8] for the
462 role of this category in sub-Riemannian geometry.)

463 *Proof.* The system (3.10) is equivalent to

$$464 \quad (4.1) \quad \begin{cases} \omega' = \omega, \\ \rho' = -\rho(1 + \Omega \tilde{A}(\Omega, \xi)), \\ \xi' = \Omega \tilde{C}(\Omega, \xi). \end{cases}$$

465 It has the same trajectories, and thus the same Poincaré mapping between the two
466 sections. The transition time is given by the first equation: $s(\omega_0) = \ln(\omega_f/\omega_0)$. (The
467 singular-regular transition occurs when $\omega_0 \rightarrow 0$, and the transition time tends to
468 infinity.) Still noting $u = \rho\omega$, (4.1) implies

$$469 \quad (4.2) \quad \begin{cases} \Omega' = -\Omega^2 \tilde{A}(\Omega, \xi), \\ \xi' = \Omega \tilde{C}(\Omega, \xi), \end{cases}$$

470 that we want to integrate from an initial condition on Π_0 in time $s(\omega_0)$. We extend
471 this system by the trivial equation $\omega'_0 = 0$, and denote φ its associated flow. Then,
472 $T(\omega_0, \xi_0) = \varphi(\ln(\omega_f/\omega_0), \omega_0, \rho_0\omega_0, \xi_0)$ (remember that on Π_0 , $\Omega_0 = \rho_0\omega_0$). It is not
473 the form we are looking for since $\ln(\omega/\omega_0)$ is not regular at $\omega_0 = 0$, but we have the
474 following estimate on the u coordinate of the flow.

475 **LEMMA 4.3.** *There exists a constant M such that, for small enough $\omega_0 > 0$,
476 $\xi \in D$, and integration time $t \leq \ln(\omega_f/\omega_0)$,*

$$477 \quad 0 \leq \Omega(t, \omega_0, \rho_0\omega_0, \xi_0) \leq M\omega_0.$$

478 *Proof.* Compare the dynamics of Ω in (4.2) with $v' = -v^2$, which integrates
479 according to

$$480 \quad v(t, v_0) = \frac{v_0}{1 + v_0 t}$$

481 for $v_0 > 0$. So

$$482 \quad v(\ln(\omega_f/\omega_0), \rho_0\omega_0) = \frac{\rho_0\omega_0}{1 + \rho_0\omega_0 \ln(\omega_f/\omega_0)},$$

483 hence the estimate as $\omega_0 \ln(\omega_f/\omega_0)$ is small enough for small enough $\omega_0 > 0$. \square

484 Let us make a change of time, and consider the following rescaled system:

$$485 \quad (4.3) \quad \begin{cases} \omega'_0 = 0, \\ \Omega' = -(\Omega^2/\omega_0)\tilde{A}(\Omega, \xi), \\ \xi' = (\Omega/\omega_0)\tilde{C}(\Omega, \xi). \end{cases}$$

486 For $\omega_0 > 0$, its flow $\tilde{\varphi}$ is well defined and the Poincaré mapping is obtained by
487 evaluating it in time $\omega_0 \ln(\omega_f/\omega_0)$:

$$488 \quad T(\omega_0, \xi_0) = \tilde{\varphi}(\omega_0 \ln(\omega_f/\omega_0), \omega_0, \rho_0\omega_0, \xi_0).$$

489 We make a blow-up on $\{\Omega = \omega = 0\}$ to prove that T has the required regularity. Set
 490 $f(\Omega, \omega, \xi) = (\eta, \omega, \xi)$ with $\eta = \Omega/\omega$: in coordinates (ω, η, ξ) , the pulled back system
 491 writes

$$492 \quad (4.4) \quad Z : \begin{cases} \omega'_0 = 0, \\ \eta' = -\eta^2 \tilde{A}(\eta\omega_0, \xi), \\ \xi' = \eta \tilde{C}(\eta\omega_0, \xi). \end{cases}$$

493 The vector field Z is actually smooth. The blow-up map f sends the cone $-\eta_0\omega \leq$
 494 $\Omega \leq \eta_0\omega$ onto the rectangle $-\eta_0 \leq \eta \leq \eta_0$, $-\omega_0 \leq \omega \leq \omega_0$. According to the previous
 495 lemma, we only need to evaluate its flow $\hat{\varphi}(t, \omega_0, \eta_0, \xi_0)$ on a band $\omega_0 \in [-\omega_1, \omega_1]$,
 496 $\eta_0 \in [-M, M]$, $\xi \in D$, to compute $\tilde{\varphi}$ in time $\omega_0 \ln(\omega_f/\omega_0)$. As $\hat{\varphi} = (\hat{\eta}, \hat{\xi})$ is smooth
 497 on such a band, we eventually get

$$498 \quad T(\omega_0, \xi_0) = (\hat{\eta}(\omega_0 \ln(\omega_f/\omega_0), \omega_0, \rho_0, \xi_0), \hat{\xi}(\omega_0 \ln(\omega_f/\omega_0), \omega_0, \rho_0, \xi_0)),$$

499 which has the desired regularity. \square

500 **5. Application to mechanical systems.** In this section, we particularize our
 501 study to mechanical systems associated with a potential. We go further in the specific
 502 case of the potential of the restricted three body problem. Let Q be an open subset
 503 of the plane \mathbf{R}^2 , let $g : TQ = Q \times \mathbf{R}^2 \rightarrow \mathbf{R}^2$ be a smooth function on the (trivial)
 504 tangent bundle, and consider the following controlled mechanical system on $M = TQ$:

$$505 \quad (5.1) \quad \ddot{q}(t) + g(q(t), \dot{q}(t)) = u(t), \quad u_1^2(t) + u_2^2(t) \leq 1.$$

506 A simple rescaling allows to take into account a more general constraint on the control,
 507 $|u(t)| \leq \varepsilon$, for any positive ε . Given a smooth potential $V : Q \rightarrow \mathbf{R}$, an important
 508 particular case of such a mechanical system is obtained for $g(q, v) = \nabla V(q)$, in which
 509 case g is independent of the velocity coordinate v (this corresponds to a system with
 510 kinetic energy $\frac{v^2}{2}$). System (5.1) is control-affine of the form (2.1) studied in the
 511 previous sections with

$$512 \quad F_0(q, v) = v \frac{\partial}{\partial q} - g(q, v) \frac{\partial}{\partial v}, \quad F_1(q, v) = \frac{\partial}{\partial v_1}, \quad F_2(q, v) = \frac{\partial}{\partial v_2}.$$

513 **PROPOSITION 5.1.** *Minimum time controls of (5.1) are piecewise smooth with a*
 514 *finite number of singularities. At such singularities, the control rotates instantaneously*
 515 *of an angle π (generating so-called " π -singularities" [10]).*

516 *Proof.* One checks that $\{F_1, F_2, F_{01}, F_{02}\}$ have rank four at any point of M , so
 517 assumption (A) holds. As $H_{12} = 0$ everywhere, $\Sigma = \Sigma_-$: contacts of minimum time
 518 extremals with Σ are isolated according to Proposition 3.1, so there are finitely many
 519 of them, and at such points $u(\bar{t}+) = -u(\bar{t}-)$ by virtue of (3.11). \square

520 Theorems 3.3 and 4.1 also apply. Every initial condition leading to a π -singularity
 521 has a neighbourhood that can be stratified, with a codimension one stratum leading
 522 to neighbouring π -singularities. The extremal flow is continuous on this neighbour-
 523 hood, and crossing this stratum generates logarithmic (in the sense of Theorem 4.1)
 524 singularities on the flow.

525 An important application is the minimum time control of the elliptic restricted
 526 three body problem [22]. Let $\mu \in (0, 1)$ be the ratio of the two primary masses, and
 527 let $e \in [0, 1)$ be the eccentricity; the elliptic restricted problem seeks the trajectory

528 of a third body whose motion is influenced by the two primary masses, while these
 529 masses are not influenced by the third negligible one. The two primaries are assumed
 530 to be on elliptic orbits of common eccentricity $e \in [0, 1)$ and common focus equal to
 531 their center of mass set at the origin (see Figure 4). Let us denote q^1 and q^2 the
 532 positions, depending on time, of the two primaries. Let \mathcal{Q} denote the open subset of
 533 the time-position space

$$534 \quad \mathcal{Q} = \{(t, q) \in \mathbf{R} \times \mathbf{R}^2 \mid q \neq q^1(t) \text{ and } q \neq q^2(t)\}$$

535 outside collisions. On $\mathcal{Q} \times \mathbf{R}^2$, the dynamics describing the controlled motion of the
 536 third body is

$$537 \quad (5.2) \quad \ddot{q}(t) + \nabla_q V_{\mu, e}(t, q(t)) = u(t),$$

538 where the time-dependent potential is

$$539 \quad V_{\mu, e}(t, q) = \frac{1 - \mu}{|q - q^1(t)|} + \frac{\mu}{|q - q^2(t)|}.$$

540 Note that q^1 and q^2 depend on the eccentricity e prescribing the motion of the two
 541 primaries, hence the dependence of the potential both on μ and e . A remarkable
 542 situation occurs when $e = 0$. The two primaries are in circular motion around their
 543 center of mass, and the system can be made autonomous by going into the moving
 544 frame attached to the rotating bodies. In this frame, still denoting q the position
 545 (now related to moving axes), the dynamics is exactly of the form (5.1) with

$$546 \quad g(q, v) = (1 - \mu) \frac{(q_1 + \mu, q_2)}{[(q_1 + \mu)^2 + q_2^2]^{3/2}} + \mu \frac{(q_1 - 1 + \mu, q_2)}{[(q_1 - 1 + \mu)^2 + q_2^2]^{3/2}} - q + 2(-v_2, v_1),$$

547 and $Q = \mathbf{R}^2 \setminus \{(-\mu, 0), (1 - \mu, 0)\}$. We refer to [9] for further details on the controlled
 548 circular restricted three body problem. As stated at the beginning of the section,
 549 Proposition 3.1 as well as Theorems 3.3 and 4.1 apply to the minimum time control
 550 of the circular restricted problem. Besides, it turns that Proposition 5.1 remains
 551 true for the more general elliptic restricted problem. The proof is based on a direct
 552 estimation *à la Sturm* of the time between two singularities, and provides a global
 553 bound on the number of these singularities. Let $q : [0, t_f] \rightarrow \mathbf{R}^2$ be a minimum time
 554 trajectory of the elliptic restricted three body problem (5.2). Let us denote

$$555 \quad \delta_1 = \min_{[0, t_f]} |q(t) - q^1(t)|, \quad \delta_2 = \min_{[0, t_f]} |q(t) - q^2(t)|,$$

556 and

$$557 \quad \delta_{12} = \frac{\delta_1 \delta_2}{[(1 - \mu)\delta_2^3 + \mu\delta_1^3]^{1/3}}.$$

558 **PROPOSITION 5.2.** *Singularities of minimum time trajectories of the elliptic re-*
 559 *stricted three body problem are π -singularities. The number of π -singularities for a*
 560 *minimum time trajectory is bounded above by $\lfloor t_f / (\pi\delta_{12}^{3/2}) \rfloor$, where t_f is the minimum*
 561 *time.*

562 In the circular restricted case ($e = 0$), this proposition provides a global bound on
 563 the number of heteroclinic connections of the system after blow-up and time change
 564 defined in Section 3; each π -singularity is associated with a pair of hyperbolic equilibria

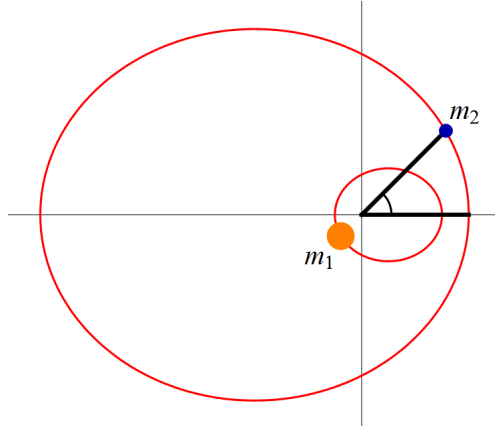


FIG. 4. *Elliptic restricted three body problem. The two primary masses, m_1 and m_2 , are on elliptic orbits of common eccentricity and common focus (located at their center of mass).*

565 (\bar{z}_-, \bar{z}_+) , and going from one π -singularity to another generates a connection between
 566 \bar{z}_+^i and \bar{z}_-^{i+1} . Not surprisingly, this bound is expressed in terms of the distance to the
 567 primaries, that is to the singularities of the original dynamics. An interesting open
 568 question is to provide an estimate of the distance to the collisions—and thus a more
 569 explicit bound on the number of π -singularities—in terms of the boundary conditions
 570 in the position-velocity phase space of the restricted problem. Note also that when
 571 $\mu = 0$, we go back to the Kepler problem and $\delta_1 = \delta_{12}$ is the distance to the collision.
 572 The proof the proposition uses the following lemma.

573 LEMMA 5.3. *Let us consider the minimum-time control of*

$$574 \quad (5.3) \quad \ddot{q}(t) + \nabla_q V(t, q(t)) = u(t),$$

575 *where V is a smooth potential defined on a open subset $O \subset \mathbf{R}^3$. Let $A(t, q)$ be a*
 576 *symmetric matrix of order n whose entries depend continuously on $(t, q) \in O$ such*
 577 *that*

$$578 \quad A(t, q) \geq \nabla_{qq}^2 V(t, q), \quad (t, q) \in O.$$

579 *The following statement holds. Singularities of minimum time trajectories of (5.3)*
 580 *are π -singularities. If $\bar{t}_1 < \bar{t}_2$ are two such singularities, if $A(t, q(t)) > \nabla_{qq}^2 V(t, q(t))$*
 581 *for some $t \in [\bar{t}_1, \bar{t}_2]$, there exists a non-trivial solution of $\ddot{y}(t) + A(t, q(t))y(t) = 0$ that*
 582 *vanishes both at \bar{t}_1 and $\bar{t}'_2 < \bar{t}_2$.*

583 *Proof.* Applying Pontrjagin maximum principle to (5.3), one gets the maximized
 584 (time dependent) Hamiltonian

$$585 \quad H(t, q, v, p_q, p_v) = p_q \cdot v - p_v \cdot \nabla_q V(t, q) + |p_v|,$$

586 and $u = p_v/|p_v|$ whenever p_v is not zero. As the equation on p_v is a second order
 587 linear one,

$$588 \quad \ddot{p}_v(t) + \nabla_{qq}^2 V(t, q(t))p_v(t) = 0,$$

589 if p_v and \dot{p}_v vanish simultaneously then p_v is identically zero: this is impossible since
 590 $p_q = -\dot{p}_v$ would also vanish, leading to $p = (p_q, p_v)$ identically zero, a proscribed case
 591 when minimizing time. So $\dot{p}_v \neq 0$ when $p_v = 0$, and the zeros of p_v are isolated.
 592 At such a point, the ratio $p_v/|p_v|$ has opposite left and right limits, resulting in a
 593 π -singularity. Sturm's comparison Theorem [16] allows to conclude. \square

594 *Proof (of Proposition 5.2).* Let

$$595 \quad A(t, q) = \begin{pmatrix} 1 + \frac{1-\mu}{|q-q^1(t)|^3} + \frac{\mu}{|q-q^2(t)|^3} & 0 \\ 0 & \frac{1-\mu}{|q-q^1(t)|^3} + \frac{\mu}{|q-q^2(t)|^3} \end{pmatrix}.$$

596 A straightforward calculation shows that

$$597 \quad \det(A(t, q) - \nabla_{qq}^2 V_\mu(t, q)) = 3 \left[(1-\mu) \frac{(q_2 - q_2^1(t))^2}{|q - q^1(t)|^5} + \mu \frac{(q_2 - q_2^2(t))^2}{|q - q^2(t)|^5} \right] > 0$$

598 for (t, q) in \mathcal{Q} . By the previous lemma, the interval between two singularities is greater
599 than the time interval between two zeros of the scalar equation

$$600 \quad (5.4) \quad \ddot{y}(t) + \left(\frac{1-\mu}{|q(t) - q^1(t)|^3} + \frac{\mu}{|q(t) - q^2(t)|^3} \right) y(t) = 0.$$

601 As

$$602 \quad \frac{1-\mu}{|q(t) - q^1(t)|^3} + \frac{\mu}{|q(t) - q^2(t)|^3} \leq \frac{1-\mu}{\delta_1^3} + \frac{\mu}{\delta_2^3},$$

603 a solution of (5.4) cannot have consecutive zeros in an interval of length smaller than

$$604 \quad \frac{\pi}{\sqrt{\frac{1-\mu}{\delta_1^3} + \frac{\mu}{\delta_2^3}}} = \pi \delta_{12}^{3/2}$$

605 by Sturm comparison again. \square

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