A Bellman approach for regional optimal control problems in $\mathbb{R}^N$

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Abstract

This article is a continuation of a previous work where we studied infinite horizon control problems for which the dynamic, running cost and control space may be different in two half-spaces of some euclidian space $\mathbb{R}^N$. In this article we extend our results in several directions: (i) to more general domains; (ii) by considering finite horizon control problems; (iii) by weaken the controlability assumptions. We use a Bellman approach and our main results are to identify the right Hamilton-Jacobi-Bellman Equation (and in particular the right conditions to be put on the interfaces separating the regions where the dynamic and running cost are different) and to provide the maximal and minimal solutions, as well as conditions for uniqueness. We also provide stability results for such equations.

Key-words: Optimal control, discontinuous dynamic, Bellman Equation, viscosity solutions.

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1 Introduction

This article is a continuation of [6] where we studied infinite horizon control problems for which the dynamic, running cost and control space may be different in two half-spaces of some euclidian space $\mathbb{R}^N$. This study was made through the Bellman approach and our main results were to identify the right Hamilton-Jacobi-Bellman Equation (and in particular the right conditions to be put on the hyperplane separating the regions where the dynamic and running cost are different) and to provide the maximal and minimal solutions, as well as conditions for uniqueness. The aim of the present paper is three-fold: (i) to extend these results to more general domains; (ii) to consider also finite horizon control problems; (iii) last but not least, to weaken the controlability assumption made in [6]. We also emphasize the stability properties for such equations which are a little bit different from the classical ones.

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To be more specific, we recall that, in the classical theory (see for example Lions [27], Fleming & Soner [21], Bardi & Capuzzo Dolcetta [4]), Hamilton-Jacobi-Bellman Equation for finite horizon control problems in the whole space $\mathbb{R}^N$ have the form

$$u_t + H(x, t, Du) = 0 \quad \text{in } \mathbb{R}^N \times (0, T),$$

where the Hamiltonian $H$ is typically given by

$$H(x, t, p) := \sup_{\alpha \in A} \{ -b(x, t, \alpha) \cdot p - l(x, t, \alpha) \}.$$  

(1.2)

The control space $A$ is assumed to be compact, the dynamic $b$ and running cost $l$ are supposed to be continuous functions which are Lipschitz continuous in $x$, so that $H$ is continuous and has suitable properties ensuring existence and uniqueness of a solution to (1.1).

In this paper, as we already mentioned above, we have different dynamics and running costs in different regions. In other words, the functions $b$ and $l$ are not assumed to be continuous anymore when crossing the boundaries of the different regions, which implies that the Hamiltonian $H$ in (1.2) also presents discontinuities. Hence, getting suitable comparison and uniqueness results for (1.1) in this setting is not obvious at all and the aim of this paper is to give precise answers to these questions.

To be more precise, we are going to decompose $\mathbb{R}^N$ using a collection $(\Omega_i)_{i \in I}$ of regular open subsets of $\mathbb{R}^N$ such that each point $x \in \mathbb{R}^N$ either lies inside one (and only one) $\Omega_i$, or is located on the boundary of exactly two sets $\Omega_i$. Because of the (regularity) assumptions we are going to use, we can in fact reduce this collection to two domains $\Omega_1, \Omega_2$: we refer to Section 6 for comments on this reduction. More precisely we assume that

$$(H_{\Omega}) \ \mathbb{R}^N = \Omega_1 \cup \Omega_2 \cup \mathcal{H} \text{ with } \Omega_1 \cap \Omega_2 = \emptyset \text{ and } \mathcal{H} = \partial \Omega_1 = \partial \Omega_2 \text{ is a } W^{2,\infty} \text{-hypersurface in } \mathbb{R}^N.$$  

For $x \in \mathcal{H}$ we denote by $n_i(x)$ the unit normal vector pointing outwards $\Omega_i$, for $i = 1, 2$. Of course, $n_1(\cdot) = -n_2(\cdot)$ on $\mathcal{H}$.

In each $\Omega_i$, $i = 1, 2$, we have a ”classical” finite-horizon control problem and the equation can be written as

$$u_t + H_i(x, t, Du) = 0 \quad \text{in } \Omega_i \times (0, T),$$

(1.3)

for some $T > 0$, where $H_i$ is given by

$$H_i(x, t, p) := \sup_{\alpha_i \in A_i} \{ -b_i(x, t, \alpha_i) \cdot p - l_i(x, t, \alpha_i) \}.$$  

(1.4)

The $b_i, l_i$ are at least continuous functions defined on $\mathbb{R}^N \times (0, T) \times A_i$, the control space $A_i$ being compact metric spaces; precise assumptions will be given later on.

Of course, one has to write down an equation on the whole space $\mathbb{R}^N$ (and in particular on $\mathcal{H}$) and this can be done using viscosity solutions’ theory ([32], [5], [4]). One can consider Equation (1.1) with $H = H_i$ on $\Omega_i$ and use Ishii’s definition of viscosity solutions for discontinuous Hamiltonians (cf. [25]) which reads

$$\left( u^\ast \right)_t + H_i(x, t, Du^\ast) = 0 \quad \text{in } \mathbb{R}^N \times (0, T) \quad \text{for subsolutions } u \quad \text{and}$$

$$\left( v_i \right)_t + H_i(x, t, Dv_i) = 0 \quad \text{in } \mathbb{R}^N \times (0, T) \quad \text{for supersolutions } v,$$

for $i = 1, 2$.  


where the “upper-star” denotes the upper semi-continuous envelope while the “lower-star” denotes the lower semi-continuous envelope. Following this means that we have to complement Equations (1.3) by
\[
\min\{u_t + H_1(x, t, Du), u_t + H_2(x, t, Du)\} \leq 0 \quad \text{on } \mathcal{H} \times (0, T),
\]
\[
\max\{u_t + H_1(x, t, Du), u_t + H_2(x, t, Du)\} \geq 0 \quad \text{on } \mathcal{H} \times (0, T).
\]

A first question we address in [6] is to investigate the uniqueness properties for (1.1) or equivalently (1.3)-(1.5)-(1.6). Unfortunately, and this leads us to describe the second aspect of [6], one can define (in general) several value functions for the associated control problem(s) and all the natural value functions satisfy (1.3)-(1.5)-(1.6). We are not going to describe these different control problems in the introduction: we refer the reader to Section 2. But we just mention that the differences mainly concern the “admissible” control or dynamics on the interface \(\mathcal{H}\): this set can be chosen in different ways creating such non-uniqueness and (to our point of view) there is no criterion to declare one of these value functions more natural than the others.

There are more and more articles on Hamilton-Jacobi-Bellman Equations or control problems on multi-domains (also called stratified domains). We start by recalling the pioneering work by Dupuis [19] who use similar methods to construct a numerical method for a calculus of variation problem with discontinuous integrand. Problems with a discontinuous running cost were addressed by either Garavello and Soravia [22, 23], or Camilli and Siconolfi [14] (even in an \(L_\infty\)-framework) and Soravia [33]. To the best of our knowledge, all the uniqueness results use a special structure of the discontinuities as in [17, 18, 24] or an hyperbolic approach as in [3, 16]. Recent works on optimal control problem on stratified domains are the ones of Bressan and Hong [12] but also Barnard and Wolenski [9] and Rao and Zidani [28] (who mention a forthcoming work with Siconolfi [29]): in these three last works, uniqueness results are provided by a completely different method than ours, which relies on control arguments. The advantage of their methods is to allow them to handle more general stratified domains (non-smooth domains with multiple junctions) but with more restrictive controllability assumptions and without the stability results we can provide. We finally remark that problems on network (see [31], [2], [13]) share the same kind of difficulties: indeed one has to take into account the junctions as we have to deal with the interface \(\mathcal{H}\).

The paper is organized as follows: in Section 2 we introduce the main ingredients and assumptions for the control problem(s) and following [6] we recall how to define the dynamic and cost in a proper way. We define two different value functions \((U^-)\) and \((U^+)\). The difference with [6] is that \(U^-\), \(U^+\) are not necessarily continuous since we have weakened the controllability assumption and the first consequence is that the connections with the Bellman Equation (1.3)-(1.5)-(1.6) in Section 3 has to be stated in terms of discontinuous viscosity solutions (cf. Theorem 3.3). Then, still in Section 3 we provide properties, satisfied either by \(U^+\) or by general sub and supersolutions which play a key role in order to obtain comparison results. Uniqueness-comparison properties are described in Section 4: we slightly modify the approach of [6] by emphasizing the role of a “local comparison result” which is given in the Appendix. As in [6] this “local comparison result” relies on the regularization of the subsolutions but this is a little bit more technical here since the controllability assumption is replaced by a weaker hypothesis (“controlability in the normal direction” on \(\mathcal{H}\)). In Section 5 we study the stability properties of the problems we have introduced in Section 3 for the problem satisfied by \(U^-\), it is a “classical” stability result, but contrarily to the standard results in viscosity solutions’ theory, we face a difficulty because of the discontinuity...
on \( \mathcal{H} \), difficulty which is solved in an unusual way by the controlability assumption in the normal direction. For the problem satisfied by \( U^+ \), we prove the stability of controlled trajectories and costs, a rather delicate result since we have to show that the limit of trajectories with “regular strategies” (a notion which is defined in Section 2) is a trajectory with a “regular strategy”. In this second case, we have no pde approach and therefore this is the only kind of results we may hope to have. Finally Section 3 is devoted to describe several extensions, in particular to time-dependent multi-domains problems.

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2 The optimal control problem

The control problem — We fix \( T > 0 \) and consider that, on each domain \( \Omega_i \) \( (i = 1, 2) \) we have a controlled dynamic given by \( b_i : \overline{\Omega_i} \times [0, T] \times A_i \rightarrow \mathbb{R}^N \), where \( A_i \) is the compact metric space where the control takes its values. We have also a running cost \( l_i : \overline{\Omega_i} \times [0, T] \times A_i \rightarrow \mathbb{R} \). Throughout the paper, we make the following assumption on the initial cost:

\((H_g)\) The function \( g \) is bounded and continuous in \( \mathbb{R}^N \).

Our main assumptions for the control problem are the following

\((H^1_C)\) For any \( i = 1, 2, A_i \) is a compact metric space and \( b_i : \overline{\Omega_i} \times [0, T] \times A_i \rightarrow \mathbb{R}^N \) is a continuous bounded function. More precisely there exists \( M_b > 0 \), such that for any \( x \in \mathbb{R}^N, s \in [0, T] \) and \( \alpha_i \in A_i, i = 1, 2, \)

\[ |b_i(x, s, \alpha_i)| \leq M_b. \]

Moreover there exists \( L_b \in \mathbb{R} \) such that, for any \( z, z' \in \overline{\Omega_i}, s, s' \in [0, T] \) and \( \alpha_i \in A_i, i = 1, 2, \)

\[ |b_i(z, s, \alpha_i) - b_i(z', s', \alpha_i)| \leq L_b(|z - z'| + |s - s'|). \]

\((H^2_C)\) For any \( i = 1, 2, \) the function \( l_i : \overline{\Omega_i} \times [0, T] \times A_i \rightarrow \mathbb{R}^N \) is a uniformly continuous, bounded function. More precisely there exists \( M_l > 0 \), such that for any \( x \in \mathbb{R}^N, s \in [0, T] \) and \( \alpha_i \in A_i, i = 1, 2, \)

\[ |l_i(x, s, \alpha_i)| \leq M_l. \]

Moreover there exists a modulus of continuity \( m_l : [0, +\infty) \rightarrow [0, +\infty) \) such that, for any \( z, z' \in \overline{\Omega_i}, s, s' \in [0, T] \) and \( \alpha_i \in A_i, i = 1, 2, \)

\[ |l_i(z, s, \alpha_i) - l_i(z', s', \alpha_i)| \leq m_l(|z - z'| + |s - s'|). \]

\((H^3_C)\) For each \( i = 1, 2, z \in \overline{\Omega_i}, \) and \( s \in [0, T], \) the set \( \{ (b_i(z, s, \alpha_i), l_i(z, s, \alpha_i)) : \alpha_i \in A_i \} \) is closed and convex.
There is a $\delta > 0$ such that for any $i = 1, 2$, $z \in \mathcal{H}$ and $s \in [0, T]$

$$B_i(z, s) \cdot n_i(z) \supset [-\delta, \delta] \quad (2.1)$$

where $B_i(z, s) := \{b_i(z, s, \alpha_i) : \alpha_i \in A_i\}$.

Assumption ($H_1^C$) and ($H_2^C$) are the classical hypotheses used in control problems. Hypothesis ($H_4^C$) expresses some controllability condition but only in the normal direction when the point $x$ belongs to the boundaries shared by the sets $\Omega_i$. In the sequel, we refer to ($H_C$) as the intersection of all the four hypotheses ($H_1^C$)–($H_4^C$).

**Boundary dynamics** — In order to define the controlled dynamics and trajectories which may stay for a while on the common boundary $\mathcal{H}$, we introduce the boundary dynamic as follows: if $s \in [0, T]$, $z \in \mathcal{H}$ we set

$$b_H(z, s, a) = b_H(z, s, (\alpha_1, \alpha_2, \mu)) := \mu b_1(z, s, \alpha_1) + (1 - \mu) b_2(z, s, \alpha_2),$$

where $\mu \in [0, 1]$, $\alpha_1 \in A_1$, $\alpha_2 \in A_2$. For any $z \in \mathcal{H}$ and $s \in [0, T]$ we denote by

$$A_0(z, s) := \{a = (\alpha_1, \alpha_2, \mu) : b_H(z, s, (\alpha_1, \alpha_2, \mu)) \cdot n_1(z) = 0\},$$

and the associated cost on $\mathcal{H}$ is

$$l_H(z, s, a) = l_H(z, s, (\alpha_1, \alpha_2, \mu)) := \mu l_1(z, s, \alpha_1) + (1 - \mu) l_2(z, s, \alpha_2).$$

Notice that the dynamic and cost on $\mathcal{H}$ are not symmetric if one swaps the indices 1 and 2 (although this could be overcome by changing also $\mu$).

**Trajectories** — We are going to define the trajectories of our optimal control problem by using the approach through differential inclusions which is rather convenient here. This approach has been introduced in [34] (see also [1]) and has become now classical.

Our trajectories $X_{x,t}(\cdot) = ((X_{x,t})_1, (X_{x,t})_2, \ldots, (X_{x,t})_N)(\cdot)$ are Lipschitz continuous functions which are solutions of the following differential inclusion

$$\dot{X}_{x,t}(s) \in \mathcal{B}(X_{x,t}(s), t - s) \quad \text{for a.e. } s \in [0, t); \quad X_{x,t}(0) = x \quad (2.2)$$

where

$$\mathcal{B}(z, s) := \begin{cases} B_1(z, s) & \text{if } z \in \Omega_i, \\ co(B_1(z, s) \cup \mathcal{B}_2(z, s)) & \text{if } z \in \mathcal{H}, \end{cases} \quad (2.3)$$

the notation $co(E)$ referring to the convex closure of the set $E \subset \mathbb{R}^N$. We point out that if the definition of $\mathcal{B}(z, s)$ is natural when $z \in \Omega_i$, it is dictated by the assumptions to obtain the existence of a solution to $\dot{X}_{x,t}(s)$ for $z \in \mathcal{H}$ (see below).

As we see, our controls $a(\cdot)$ can take two forms: either $a(s)$ belongs to one of the control sets $A_i$; or it can be expressed as a triple $(\alpha_1, \alpha_2, \mu) \in A_1 \times A_2 \times [0, 1]$. Hence, in order to define globally a control, we introduce the compact set

$$A := A_1 \times A_2 \times [0, 1]$$
and define a control as being a function of $L^\infty(0, t; A)$ which can be seen as a subset of $A := L^\infty(0, T; A)$. Let us define
\[
\mathcal{E}_i := \{ s \in (0, t) : X_{x,t}(s) \in \Omega_i \}, \quad \mathcal{E}_H := \{ s \in (0, t) : X_{x,t}(s) \in \mathcal{H} \},
\]
where actually these sets depend on $(x, t)$ but we shall omit this dependence for the sake of notations. We then have the following

**Theorem 2.1.** Assume $(H_{\Omega}), (H^1_C), (H^2_C)$ and $(H^3_C)$. Then

1. For each $x \in \mathbb{R}^N$, $t \in [0, T)$ there exists a Lipschitz function $X_{x,t} : [0, t] \rightarrow \mathbb{R}^N$ which is a solution of the differential inclusion \((2.2)\).

2. For each solution $X_{x,t}(\cdot)$ of \((2.2)\), there exists a control $a(\cdot) \in A$ such that for a.e. $s \in (t, T)$
\[
\dot{X}_{x,t}(s) = \sum_{i=1,2} b_i(X_{x,t}(s), t-s, \alpha_i(s))1_{\mathcal{E}_i}(s) + b_H(X_{x,t}(s), t-s, a(s))1_{\mathcal{E}_H}(s) \tag{2.4}
\]

where $a(s) = (\alpha_1(s), \alpha_2(s), \mu(s))$ if $X_{x,t}(s) \in \mathcal{H}$.

3. If $e(\cdot) = n_1(\cdot)$ or $n_2(\cdot)$ we have
\[
b_H(X_{x,t}(s), t-s, a(s)) \cdot e(X_{x,t}(s)) = 0 \quad \text{for a.e. } s \in \mathcal{E}_H.
\]

In other words, $a(s) \in A_0(X_{x,t}(s), t-s)$ for a.e. $s \in \mathcal{E}_H$.

**Proof.** The proof is done exactly as in [6], the only minor modification consisting in adding the time variable in the vector field $b$. \hfill \Box

**Regular and Singular Dynamics —** It is worth remarking that, in Theorem 2.1, a solution $X_{x,t}(\cdot)$ can be associated to several controls $a(\cdot)$. So, to set properly the control problem we introduce the set $T_{x,t}$ of admissible controlled trajectories starting from $x$,
\[
T_{x,t} := \{ (X_{x,t}(\cdot), a(\cdot)) \in \text{Lip}(0, t; \mathbb{R}^N) \times A \text{ such that } (2.4) \text{ is fulfilled and } X_{x,t}(0) = x \}
\]

Given $(z, s) \in \mathcal{H} \times [0, t]$, we call singular a dynamic $b_H(z, s, a)$ with $a = (\alpha_1, \alpha_2, \mu) \in A_0(z, s)$ when
\[
b_1(z, s, \alpha_1) \cdot n_1(z) < 0, \quad b_2(z, s, \alpha_2) \cdot n_2(z) < 0.
\]

Conversely, the regular dynamics are those for which the $b_i(z, s, \alpha_i) \cdot n_i(z) \geq 0$ ($i = 1, 2$). The set of regular controls is denoted by
\[
A^{\text{reg}}_0(z, s) := \{ a = (\alpha_1, \alpha_2, \mu) \in A_0(z, s) ; b_i(z, s, \alpha_i) \cdot n_i(z) \geq 0, \quad i = 1, 2 \},
\]

and the regular trajectories are defined as
\[
T^{\text{reg}}_{x,t} := \{ (X_{x,t}(\cdot), a(\cdot)) \in T_{x,t} ; \text{ for a.e. } s \in \mathcal{E}_H, a(s) \in A^{\text{reg}}_0(X(s), t-s) \}.
\]
The cost functional – Our aim is to minimize a finite horizon cost functional such that we respectively pay \( l_i \) if the trajectory is in \( \Omega_i \), and \( l_H \) if it is on \( H \). The final cost is given by \( g \).

More precisely, the cost associated to \( (X_{x,t}(\cdot), a) \in T_{x,t} \) is
\[
J(x, t; (X_{x,t}, a)) := \int_0^t \ell(X_{x,t}(s), t - s, a(s)) \, ds + g(X_{x,t}(t))
\]
(2.5)

where the Lagrangian is given by
\[
\ell(X_{x,t}(s), t - s, a(s)) := \sum_{i=1,2} l_i(X_{x,t}(s), t - s, \alpha_i(s)) \mathbf{1}_{E_i}(s) + l_H(X_{x,t}(s), t - s, a(s)) \mathbf{1}_{E_H}(s).
\]
(2.6)

The value functions – For each \( x \in \mathbb{R}^N \) and \( t \in [0, T) \), we define the following two value functions
\[
U^-(x, t) := \inf_{(X_{x,t}, a) \in T_{x,t}} J(x, t; (X_{x,t}, a)) \quad (2.7)
\]
\[
U^+(x, t) := \inf_{(X_{x,t}, a) \in T_{x,t}^{\text{reg}}} J(x, t; (X_{x,t}, a)).
\]
(2.8)

A first key result is the Dynamic Programming Principle (the proof being standard once we have the definition of trajectories, we skip it).

**Theorem 2.2.** Assume \((H_\Omega), (H^1_\Theta), (H^2_\Theta)\) and \((H^3_\Theta)\). Let \(U^-, U^+\) be the value functions defined in (2.7) and (2.8). Then for each \((x, t) \in \mathbb{R}^N \times [0, T)\), and each \( \tau \in (0, t) \), we have
\[
U^-(x, t) = \inf_{(X_{x,t}, a) \in T_{x,t}} \left\{ \int_0^\tau \ell(X_{x,t}(s), t - s, a(s)) \, ds + U^-(X_{x,t}(\tau), t - \tau) \right\}
\]
(2.9)
\[
U^+(x, t) = \inf_{(X_{x,t}, a) \in T_{x,t}^{\text{reg}}} \left\{ \int_0^\tau \ell(X_{x,t}(s), t - s, a(s)) \, ds + U^+(X_{x,t}(\tau), t - \tau) \right\}.
\]
(2.10)

We will prove that both value functions are continuous, but here it is not so immediate since we only assume controlability in the normal directions. We postpone this proof which uses some comparison for the semi-continuous envelopes.

3 The pde formulation of the problem

In order to describe what is happening on the hypersurface \( H \), we shall introduce two ”tangential Hamiltonians”, namely \( H_T, H_T^{\text{reg}} \). We introduce some notations to be clear on how they are defined.

We shall consider the tangent bundle \( T_H := \bigcup_{z \in H} \{z\} \times T_z H \) where \( T_z H \) is the tangent space to \( H \) at \( z \) (which is essentially \( \mathbb{R}^{N-1} \)). Thus, if \( \phi \in C^1(H) \), and \( x \in H \), we denote by \( D_H \phi(x) \) the gradient of \( \phi \) at \( x \), which belongs to \( T_x H \).

Also, the scalar product in \( T_z H \) will be denoted by \( \langle u, v \rangle \) (we drop the reference to \( T_z H \) for simplicity, since no confusion has to be feared in the sequel). In this definition, both vectors \( u, v \)
should belong to $T_z\mathcal{H}$ for this definition to make sense. Hence, to be precise we should use the orthogonal projection $P_z: \mathbb{R}^N \to T_z\mathcal{H}$ when at least one of the vectors $u, v$ lives in $\mathbb{R}^N$, but we shall omit this point when writing $\langle b_H(x, t, a), D\phi(x, t) \rangle$. Indeed, for any control $a$ in $A_0(x, t)$ or $A_0^{\text{reg}}(x, t)$, $b_H(x, t, a)$ can be identified with $P_z b_H(x, t, a)$ since $b_H(x, t, a)$ has no component on the normal direction to $\mathcal{H}$, by definition. To avoid confusions, the notation $u \cdot v$ will refer only to the usual euclidian scalar product in $\mathbb{R}^N$.

The Hamiltonians $H_T, H_T^{\text{reg}}$ will be written as $H_T/H_T^{\text{reg}}(x, t, p)$ where $((x, p), t) \in TH \times [0, T]$. They are defined as follows:

$$H_T(x, t, p) := \sup_{A_0(x, t)} \left\{ -\langle b_H(x, t, a), p \rangle - l_H(x, t, a) \right\},$$

$$H_T^{\text{reg}}(x, t, p) := \sup_{A_0^{\text{reg}}(x, t)} \left\{ -\langle b_H(x, t, a), p \rangle - l_H(x, t, a) \right\},$$

where $A_0(x, t), A_0^{\text{reg}}(x, t)$ have been defined above.

The definition of viscosity sub and super-solutions for $H_T$ and $H_T^{\text{reg}}$ have to be understood on $\mathcal{H}$ as follows:

**Definition 3.1.** A bounded usc function $u : \mathcal{H} \times [0, T] \to \mathbb{R}$ is a viscosity subsolution of

$$u_t(x, t) + H_T(x, t, D_H u) = 0 \quad \text{on} \quad \mathcal{H} \times [0, T]$$

if, for any $\phi \in C^1(\mathcal{H} \times [0, T])$ and any maximum point $(x, t)$ of $(z, s) \mapsto u(z, s) - \phi(z, s)$ in $\mathcal{H} \times [0, T]$, one has

$$\phi_t(x, t) + H_T(x, t, D_H \phi(x, t)) \leq 0.$$

Notice that of course, $(x, D_H \phi(x, t)) \in T\mathcal{H}$, so that this is coherent with the definition of $H_T$. A similar definition holds for $H_T^{\text{reg}}$, for supersolutions and solutions. Of course, if $u$ is defined in a bigger set containing $\mathcal{H} \times [0, T]$ (typically $\mathbb{R}^N \times [0, T]$), we have to use $u|_{\mathcal{H} \times [0, T]}$ (the restriction of $u$ to $\mathcal{H} \times [0, T]$) in this definition, a notation that we will omit when not necessary.

For the sake of clarity we introduce now a global formulation involving a complementary Hamiltonian on the interface $\mathcal{H}$. To begin with, we recall that a subsolution (resp. a supersolution of $H_T$) when $H(x, t, p) = H_1(x, t, p)$ if $x \in \Omega_1$ and $H(x, t, p) = H_2(x, t, p)$ if $x \in \Omega_2$ is a bounded usc function $u$ (resp. a bounded lsc function $v$) which satisfies

$$\begin{cases}
    u_t + H_1(x, t, D u) \leq 0 & \text{in } \Omega_1 \times (0, T), \\
    u_t + H_2(x, t, D u) \leq 0 & \text{in } \Omega_2 \times (0, T), \\
    u_t + \min\{H_1(x, t, D u), H_2(x, t, D u)\} \leq 0 & \text{in } \Gamma \times (0, T),
\end{cases}$$

resp.

$$\begin{cases}
    v_t + H_1(x, t, D v) \geq 0 & \text{in } \Omega_1 \times (0, T), \\
    v_t + H_2(x, t, D v) \geq 0 & \text{in } \Omega_2 \times (0, T), \\
    v_t + \min\{H_1(x, t, D v), H_2(x, t, D v)\} \geq 0 & \text{in } \Gamma \times (0, T)
\end{cases}.$$

Recall that since each $b_i$ is defined on $\overline{\Omega}_i \times (0, T) \times \mathbb{R}$, then $H_i$ is well-defined on $\Gamma \times (0, T)$. Next we have the following definition.
\textbf{Definition 3.2.} We say that a bounded usc function $u$ is a subsolution of
\begin{equation}
    u_t + H^-(x,t, Du) = 0 \text{ in } \mathbb{R}^N \times (0,T) \tag{3.5}
\end{equation}
\begin{equation}
    \text{resp. } u_t + H^+(x,t, Du) = 0 \text{ in } \mathbb{R}^N \times (0,T) \tag{3.6}
\end{equation}
if it satisfies (3.3) and
\begin{equation}
    u_t(x,t) + H_T(x,t, D_H u) \leq 0 \text{ on } H \times [0,T], \quad \text{resp. } u_t(x,t) + H_T^{\text{reg}}(x,t, D_H u) \leq 0 \text{ on } H \times [0,T],
\end{equation}
in the sense of Definition [3.7].
A lsc function $v$ is a supersolution of (3.5) or (3.6) if it satisfies (3.4).

Notice that in this definition, a complementary condition is required only for the subsolution, nothing more is added for the supersolution.

\subsection{Properties of $U^+$ and $U^-$}

We shall prove later on that both $U^+$ and $U^-$ are continuous, but for the moment we have to treat them a priori as discontinuous viscosity solutions of some problem. We recall that, for any bounded function $v$, the lower and upper semi-continuous envelope are defined by
\begin{equation}
    v_*(x,t) := \liminf_{(z,s)\to(x,t)} v(z,s), \quad v^*(x,t) := \limsup_{(z,s)\to(x,t)} v(z,s).
\end{equation}
Then, as we mention in the introduction the definition of viscosity solution for discontinuous solutions is modified by taking $(U^-)_*$ instead of $U^-$ for the supersolution condition, and $(U^-)^*$ instead of $(U^-)$ for the subsolution condition.

We claim that the value functions $U^-$ and $U^+$ are viscosity solutions of the Hamilton-Jacobi-Bellman problem (1.3)-(1.5)-(1.6), while they fulfill different inequalities on the hyperplane $H$.

\textbf{Theorem 3.3.} Assume $(H_g)$, $(H_H)$ and $(H_C)$. Then value functions $U^-$ and $U^+$ are both viscosity solutions of $u_t + H(x,u,Du) = 0$. Moreover, $U^-$ is a subsolution of $u_t + H^-(x,t,Du) = 0$ while $U^+$ is a subsolution of $u_t + H^+(x,t,Du) = 0$.

\textit{Proof.} The proof follows the arguments of [6] Thm 2.5] with some adaptations due to the fact that $U^-, U^+$ can be discontinuous. We briefly show how to adapt the arguments. In order to prove that $(U^-)_*$ is a supersolution we consider a point $(x,t)$ where $(U^-)_* - \phi$ reaches its minimum, $\phi$ being a smooth test function. If $x$ belongs to some $\Omega_t$, the proof is classical since everything can be done in $\Omega_t$ around the time $t$.

Thus we assume that $x \in H$ and that the minimum is strict in $B(x,r) \times (t-s, t+s)$ for some $r, s > 0$. There exists a sequence $(x_n, t_n) \in B(x,r) \times (t-s, t+s)$ which converges to $(x,t)$ such that $U^-(x_n, t_n) \to (U^-)_*(x,t)$ and by the dynamic programming principle,
\begin{equation}
    U^-(x_n, t_n) = \inf_{(X_{x_n,t_n},a) \in T_{x_n,t_n}} \left\{ \int_0^T t(X_{x_n,t_n}(s), t_n-s, a(s)) \, ds + U^-(X_{x_n,t_n}(\tau), t_n-\tau) \right\},
\end{equation}
where \( \tau < \sigma \). Using that (i) \( U^-(x_n, t_n) = (U^-)_a(x, t) + o_n(1) \) where \( o_n(1) \to 0 \), (ii) \( U^-(x_n, t_n(\tau), t_n - \tau) \geq U^-\left(X_{x_n, t_n}(\tau), t_n - \tau\right) \) and the maximum point property, we obtain

\[
\phi(x_n, t_n) + o_n(1) \geq \inf_{(X_{x_n, t_n}, a)} \left\{ \int_0^\tau \ell(X_{x_n, t_n}(s), t_n - s, a(s)) \, ds + \phi(X_{x_n, t_n}(\tau), t_n - \tau) \right\}.
\]

Now we use the expansion of \( \phi(X_{x_n, t_n}(\tau), t_n - \tau) \), and noting \( X(\cdot) = X_{x_n, t_n}(\cdot) \) for the sake of notations, we rewrite the inequality as \( o_n(1) \leq \sup \int_0^\tau \delta[\phi](s) \, ds \) where

\[
\delta[\phi](s) := \left( -l_1(X(s), t_n - s, \alpha_1(s)) - b_1(X(s), t_n - s, \alpha_1(s)) \cdot D\phi(X(s), t_n - s) + \phi_t(X(s), t_n - s) \right) 1_{E_1}(s) + \left( -l_2(X(s), t_n - s, \alpha_2(s)) - b_2(X(s), t_n - s, \alpha_2(s)) \cdot D\phi(X(s), t_n - s) + \phi_t(X(s), t_n - s) \right) 1_{E_2}(s) + \left( -l_H(X(s), t_n - s, a(s)) - b_H(X(s), t_n - s, a(s)) \cdot D\phi(X(s), t_n - s) + \phi_t(X(s), t_n - s) \right) 1_{E_H}(s)
\]

\[
\leq \left( \phi_t(X(s), t_n - s) + H_1\left(X(s), t_n - s, D\phi(X(s), t_n - s)\right) \right) 1_{E_1}(s) + \left( \phi_t(X(s), t_n - s) + H_2\left(X(s), t_n - s, D\phi(X(s), t_n - s)\right) \right) 1_{E_2}(s) + \left( \phi_t(X(s), t_n - s) + H_T\left(X(s), t_n - s, D\phi(X(s), t_n - s)\right) \right) 1_{E_H}(s).
\]

Using that \( H_1, H_2, H_T \leq \max(H_1, H_2) \) (only on \( H \) for \( H_T \)), letting \( n \to \infty \) and then dividing by \( \tau \) and sending \( \tau \) to zero, we obtain

\[
\max \left( \phi_t + H_1, \phi_t + H_2 \right)(x, t, D\phi(x, t)) \geq 0,
\]

which is the viscosity supersolution condition. The proof for \( (U^+)_a \) is exactly the same, with \( H_T \) replaced by \( H_T^{reg} \), which satisfies also \( H_T^{reg} \leq \max(H_1, H_2) \) on \( H \).

For the subsolution condition, we have to consider maximum points of \( (U^-)^* - \phi, \phi \) being again a smooth function. If such maximum point are in \( \Omega_1 \) or \( \Omega_2 \), the proof is again classical. Hence we consider the case when \( (U^-)^* - \phi \) reaches a strict local maximum at \( (x, t) \) with \( x \in H, t \in (0, T) \).

Then there exist a sequence \( (x_n, t_n) \to (x, t) \) such that \( U^-(x_n, t_n) \to (U^-)^*(x, t) \) and our first claim is that we can assume that \( x_n \in H \). Indeed, if \( x_n \in \Omega_1 \), we use assumption \( (H^2_\delta) \) : there exists \( \alpha_1 \) such that \( b_1(x, t, \alpha_1) \cdot n_1(x) = \delta \). Considering the trajectory with the constant control \( \alpha_1 \)

\[
\dot{Y}(s) = b_1(Y(s), t_n - s, \alpha_1), \quad Y(0) = x_n,
\]

it is easy to show that \( \tau_n^1 \), the first exit time of the trajectory \( Y \) from \( \Omega_1 \) tends to 0 as \( n \to +\infty \). By the Dynamic Programming Principle, denoting \( (\bar{x}_n, \bar{t}_n) = (X(\tau^1_n), t - \tau^1_n) \), we have

\[
U^-(x_n, t_n) \leq \int_0^{\tau^1_n} \ell(Y(s), t_n - s, \alpha_1) \, ds + U^-(\bar{x}_n, \bar{t}_n) = U^-(\bar{x}_n, \bar{t}_n) + o_n(1),
\]

where \( o_n(1) \to 0 \). Therefore \( U^-(\bar{x}_n, \bar{t}_n) \to (U^-)^*(x, t) \) and \( \bar{x}_n \in H \).
Assuming that \( x_n \in H \), we can use again the Dynamic Programming Principle

\[
U^-(x_n, t_n) \leq \int_0^\tau \ell(X_{x_n, t_n}(s), t_n - s, a(s)) \, ds + U^-(X_{x_n, t_n}(\tau), t_n - \tau),
\]

with constant controls \( a(s) = \alpha \) with \( b_1(x, t, \alpha_i) \cdot n_i(x) < 0 \). Arguing as above we get

\[
\phi_t(x, t) - b_1(x, t, \alpha_i) \cdot D\phi(x, t) - l_i(x, t, \alpha_i) \leq 0.
\]

Moreover, combining Assumptions \((H^3)\) and \((H^4)\), one proves easily that this inequality holds for any \( \alpha_i \) with \( b_i(x, t, \alpha_i) \cdot n_i(x) \leq 0 \).

Taking these informations into account, if we assume by contradiction that

\[
\min \{ \phi_t(x, t) + H_1(x, t, D\phi(x, t)) ; \phi_t(x, t) + H_2(x, t, D\phi(x, t)) \} > 0,
\]

this means that there exists \( \alpha_1, \alpha_2 \) with if \( b_1(x, t, \alpha_1) \cdot n_1(x) > 0 \) and \( b_2(x, t, \alpha_1) \cdot n_2(x) > 0 \) such that, for \( i = 1, 2 \)

\[
\phi_t(x, t) - b_i(x, t, \alpha_i) \cdot D\phi(x, t) - l_i(x, t, \alpha_i) > 0.
\]

For \((y, s)\) close to \((x, t)\) and for such \( \alpha_1, \alpha_2 \), we set

\[
\mu^*(y, s) := \frac{b_2(y, s, \alpha_2) \cdot n_2(y)}{b_1(y, s, \alpha_1) \cdot n_1(y) + b_2(y, s, \alpha_2) \cdot n_2(y)}.
\]

Then we solve the ode

\[
\dot{x}(s) = \mu^*(x(s), t - s)b_1(x(s), t - s - \alpha_1) + (1 - \mu^*(x(s), t - s))b_2(x(s), t - s, \alpha_2).
\]

By our hypotheses on \( b_1 \) and \( b_2 \), the right-hand side is Lipschitz continuous so that the Cauchy-Lipschitz applies and gives a solution \( x(s) \). Moreover, by our choice of \( \mu^* \), it is clear that \( 0 \leq \mu^* \leq 1 \) and that \( \dot{x}(s) \cdot n_1(x(s)) = 0 \), which implies by Gronwall’s lemma that \( s \mapsto x(s) \) remains on \( H \), at least until some time \( \tau > 0 \). Using again the Dynamic Programming Principle and the usual arguments, we are lead to

\[
\mu^*(x(t)) \left( \phi_t(x, t) - b_1(x, t, \alpha_1) \cdot D\phi(x, t) - l_1(x, t, \alpha_1) \right)
\]

\[
+ (1 - \mu^*(x(t))) \left( \phi_t(x, t) - b_2(x, t, \alpha_2) \cdot D\phi(x, t) - l_2(x, t, \alpha_2) \right) \leq 0,
\]

a contradiction.

Finally the \( H_T \)-inequality follows from the same arguments : in particular, if \( b_1(x, t, \alpha_1) \cdot n_1(x) < 0 \) and \( b_2(x, t, \alpha_1) \cdot n_2(x) < 0 \), the above \( \mu^* \)-argument can be applied readily.

The same proof works also for \((U^+)\ast\), except that some situation cannot occur since we are only considering regular dynamics.

Our next result is a (little bit unusual) supersolution property which is satisfied by \( U^+ \) on \( H \), which is done exactly as in of [6] Thm 2.7] once we have the following extension result

\[\Box\]
Lemma 3.4. Let us assume that $(\text{H}_\Omega)$ holds and let $\phi \in C^1(\mathcal{H} \times [0,T])$. Then there exists a function $\tilde{\phi} \in C^1(\mathbb{R}^N \times [0,T])$ such that $\tilde{\phi} = \phi$ in $\mathcal{H} \times [0,T]$.

Proof. The proof is rather classical so that we omit it. \qed

Theorem 3.5. we use the following notation. If $x$ is a minimum point of Lemma 3.4. Let us assume that $H$ using the normal controllability condition $(\text{H}_A)$ was used in [6].

\begin{equation}
\dot{Y}_{x,t}^i(s) = b_i(Y_{x,t}^i(s), t - s, \alpha_i(s)) \quad Y_{x,t}^i(0) = x.
\end{equation}

We argue depending on whether or not there exists a sequence $(\tau_k)$ such that $\tau_k$ converging to 0 such that $\tau_k > 0$ and $X_{x,t,\tau_k} \in \mathcal{H}$.

If it is NOT the case then this means that we are in the case A) since, for $\eta$ small enough, the trajectory $X_{x,t,\tau}(\cdot)$ stays necessarily either in $\Omega_1$ or in $\Omega_2$ on $[0,\eta]$. Therefore we can assume for instance that $X_{x,t,\tau}(\cdot) = Y_{x,t,\tau}(\cdot)$ and take $\tau = \eta$ in the above equality.

On the contrary, if IT IS the case, we can use the minimum point property: assuming without loss of generality that $\phi(x,t) = U^+(x,t)$, we extend $\phi$ to $\mathbb{R}^N \times [0,T]$ thanks to Lemma 3.4 and write, for $k$ large enough,

\begin{equation}
\tilde{\phi}(x,t) \geq \int_0^{\tau_k} \ell(X_{x,t,s}(t) - s, a(s)) ds + \tilde{\phi}(X_{x,t}(\tau_k), t - \tau_k).
\end{equation}

The rest of the proof is the same as [6] Thm 2.7: we obtain a contradiction by assuming

$\phi_{\tau}(x,t) + H^{\text{reg}}_T(x,t, D\mathcal{H}\phi(x,t)) \leq -\eta < 0$,

using the normal controllability condition $(\text{H}_{\text{C}})$ instead of the more general (and usual) one which was used in [6]. \qed

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Remark 3.6. Notice that the alternative above with \( H_{T}^{\text{reg}} \) only holds for \( U^{+} \), and not for any arbitrary supersolution (see Theorem 3.2 where \( H_{T} \) is used and not \( H_{T}^{\text{reg}} \)).

3.2 Properties of sub and supersolutions

Theorem 3.7. Assume \((H_{\Omega})\) and \((H_{C})\). If \( u : \mathbb{R}^{N} \times [0,T] \to \mathbb{R} \) is a bounded viscosity subsolution of \( u_{t} + H(x,t,Du) = 0 \), then \( u \) is a subsolution of \( u_{t} + H^{+}(x,t,Du) = 0 \).

Proof. It is enough to check the subsolution condition only on \( \mathcal{H} \) since the property clearly holds in each \( \Omega_{i} \) by definition.

We recall that \( u^{*}|_{\mathcal{H} \times [0,T]} \) is the restriction of \( u^{*} \) to \( \mathcal{H} \times [0,T] \). Let \( \phi(\cdot) \) be a \( C^{1} \)-function on \( \mathcal{H} \) and \((\bar{x},\bar{t})\) a maximum point of \( u^{*}|_{\mathcal{H} \times [0,T]} - \phi \) on \( \mathcal{H} \times [0,T] \). Our aim is then to prove that, for any \( a \in A_{0}^{\text{reg}}(\bar{x},\bar{t}) \) we have

\[
\phi_{t}(\bar{x},\bar{t}) - \langle b_{H}(\bar{x},\bar{t},a),D_{H}\phi(\bar{x},\bar{t}) \rangle - l_{H}(\bar{x},\bar{t},a) \leq 0.
\]  

(3.10)

This proof follows [6 Thm. 3.1] so that we only mention here the modifications. First, we extend \( \phi \) by \( \bar{\phi} \) given by Lemma 3.4 Then for \( \varepsilon \ll 1 \) and \((z,s) \in \mathcal{H} \times [0,T]\) we consider the function

\[
(z,s) \mapsto u(z,s) - \bar{\phi}(z,s) - \eta d_{\mathcal{H}}(z) - \frac{d_{\mathcal{H}}(z)^{2}}{\varepsilon^{2}} - |z - x|^{2} - |s - t| := u(z,s) - \psi_{\varepsilon}(z,s),
\]  

(3.11)

where \( d_{\mathcal{H}}(\cdot) \) is the signed distance function from \( \mathcal{H} \) which is positive in \( \Omega_{1} \) and negative in \( \Omega_{2} \). Note that \( d_{\mathcal{H}} \) is at least \( C^{1} \) because of \((H_{\Omega})\) and \( Dd_{\mathcal{H}} = -n_{1} = n_{2} \) on \( \mathcal{H} \).

Writing \( a = (\alpha_{1},\alpha_{2},\mu) \), we assume that we are in the situation when \( b_{1}(\bar{x},\bar{t},\alpha_{1})\cdot n_{1}(\bar{x}) < 0 \) (and the same for index 2), since the case of non-strict inequalities can be recovered by hypothesis \((H_{C})\) as in Thm. 3.3 (recall that \( a \) being a regular control, the opposite signs are forbidden). We choose \( \eta > \bar{\eta} \) where \( \bar{\eta} \) is a solution of the following equation (which has a solution under the assumption above of strict signs):

\[
\bar{\phi}_{t}(\bar{x},\bar{t}) - b_{1}(\bar{x},\bar{t},\alpha_{1}) \cdot (D\bar{\phi}(\bar{x},\bar{t}) + \eta n_{2}(\bar{x})) - l_{1}(\bar{x},\bar{t},\alpha_{1}) = 0.
\]

The rest of the proof follows the cited reference: thanks to the penalization terms, for \( \varepsilon \) small enough, \( u^{*} - \psi_{\varepsilon} \) reaches its max at some point \((x_{\varepsilon},t_{\varepsilon}) \in \Omega_{2} \times [0,T]\). Then, using the equation in \( \Omega_{2} \times [0,T] \) or on \( \mathcal{H} \) leads to

\[
\bar{\phi}_{t}(\bar{x},\bar{t}) - b_{2}(\bar{x},\bar{t},\alpha_{2}) \cdot (D\bar{\phi}(\bar{x},\bar{t}) + \eta n_{2}(\bar{x})) - l_{2}(\bar{x},\bar{t},\alpha_{2}) \leq o_{\varepsilon}(1).
\]

We let \( \varepsilon \) tend to zero first, and then \( \eta \) to \( \bar{\eta} \). Using the specific value of \( \bar{\eta} \) leads to

\[
\bar{\phi}_{t}(\bar{x},\bar{t}) - b_{H}(\bar{x},\bar{t},a) \cdot D_{H}\phi(\bar{x},\bar{t}) - l_{H}(\bar{x},\bar{t},a) \leq 0,
\]

that we interpret as (3.10) since \( b_{H}(\bar{x},\bar{t},a) \) has no component on the normal direction to \( \mathcal{H} \) and by construction, \( D_{H}(\bar{\phi}|_{\mathcal{H}}) = D_{H}\phi \).

The following lemma follows directly from [6 Lem. 3.2]
Lemma 3.8. Assume \( (H_\Omega) \) and \( (H_\cdot) \). Let \( v: \mathbb{R}^N \times [0,T] \to \mathbb{R} \) be a lsc supersolution of \( v_t + H(x,t,Dv) = 0 \) and \( u: \mathbb{R}^N \times [0,T] \to \mathbb{R} \) be a Lipschitz continuous subsolution of \( u_t + H(x,t,Du) = 0 \). Then, if \( x \in \Omega_i \) \( (i \in \{1,2\}) \), we have for all \( \sigma \in [0,t] \)

\[
v(x,t) \geq \inf_{\alpha_i(\cdot),\theta_i} \left[ \int_0^{\sigma \wedge \theta_i} l_i(Y_{x,t}^i(s),t-s,\alpha_i(s)) \, ds + v(Y_{x,t}^i(\sigma \wedge \theta_i),t-(\sigma \wedge \theta_i)) \right], \tag{3.12}
\]

and

\[
u(x,t) \leq \inf_{\alpha_i(\cdot),\theta_i} \left[ \int_0^{\sigma \wedge \theta_i} l_i(Y_{x,t}^i(s),t-s,\alpha_i(s)) \, ds + u(Y_{x,t}^i(\sigma \wedge \theta_i),t-(\sigma \wedge \theta_i)) \right], \tag{3.13}
\]

where \( Y_{x,t}^i \) is the solution of the ode (3.7) and the infima are taken on all stopping time \( \theta_i \) such that \( Y_{x,t}^i(\theta_i) \in \partial \Omega_i \) and \( \tau_i \leq \theta_i \leq \bar{\tau}_i \) where \( \tau_i \) is the first exit time of the trajectory \( Y_{x,t}^i \) from \( \Omega_i \) and \( \bar{\tau}_i \) is the one from \( \overline{\Omega}_i \).

The following important result highlights the following fundamental alternative: given \( x \in H \) either there exists an optimal strategy consisting in entering in \( \Omega_1 \) or \( \Omega_2 \), or all the optimal strategies consist in staying on \( H \) at least for a while.

Theorem 3.9. Assume \( (H_\Omega) \) and \( (H_\cdot) \). Let \( v: \mathbb{R}^N \times [0,T] \to \mathbb{R} \) be a lsc supersolution of \( v_t + H(x,t,Dv) = 0 \). Let \( \phi \in C^1(\mathcal{H} \times [0,T]) \) and \( (x,t) \) be a minimum point of \( (z,s) \mapsto v(z,s) - \phi(z,s) \). Then, the following alternative holds:

A) either there exist \( \eta > 0 \), \( i \in \{1,2\} \) and a sequence \( x_k \in \overline{\Omega}_i \) converging to \( x \) such that \( v(x_k,t) \to v(x,t) \) and, for each \( k \), there exists a control \( \alpha_k^i(\cdot) \) such that the corresponding trajectory \( Y^i_{x_k,t}(s) \in \overline{\Omega}_i \) for all \( s \in [0,\eta] \) and

\[
v(x_k,t) \geq \int_0^\eta l_i(Y^i_{x_k,t}(s),t-s,\alpha_k^i(s)) \, ds + v(Y^i_{x_k,t}(\eta),t-\eta); \tag{3.14}
\]

B) or there holds

\[
\phi_i(x,t) + H_T(x,t,D\mathcal{H}\phi_i(x,t)) \geq 0. \tag{3.15}
\]

Proof. As in [6] Thm. 3.3], we are going to prove that if A) does not hold, then necessarily the second possibility holds. Up to a standard modification of \( \phi \), we may assume that the max is strict. For \( \varepsilon > 0 \) we consider the function

\[
v(z,s) - \tilde{\phi}(z,s) - \delta d_{\mathcal{H}}(z) + \frac{d_{\mathcal{H}}(z)^2}{\varepsilon^2},
\]

where \( d_{\mathcal{H}}(\cdot) \) is the distance function from \( \mathcal{H} \) as in the proof of Theorem 3.7.

There are two cases: either for \( \varepsilon \) small enough, the minimum point \( (x_\varepsilon,t_\varepsilon) \) lies on \( \mathcal{H} \times [0,T] \) and this leads directly to (3.15) as in [6] Thm. 3.3]; or we may assume that for instance, \( x_\varepsilon \in \Omega_i \) for \( \varepsilon \) small enough. In this second case, the argument by contradiction in [6] Thm 3.3. - 2nd case] applies, using Lemma 3.8. \( \square \)
4 Uniqueness result

We first prove a local comparison result which is based on auxiliary results in the appendix. To this end, we denote by $Q(x_0,t_0)(r,h)$ the open cylinder $Q(x_0,t_0)(r,h) := B(x_0, r) \times (t_0 - h, t_0)$ where $0 < t_0 - h < t_0 < T$, whose parabolic boundary is given by

$$\partial_p Q(x_0,t_0)(r,h) := B(x_0, r) \times \{t_0 - h\} \cup \partial B(x_0, r) \times \{t_0 - h, t_0\}.$$ 

In the sequel, we assume that $x_0 \in \mathcal{H}$ and that, thanks to $(H_\Omega)$, $r$ is small enough in order that there exists a $W^{2,\infty}$-diffeomorphism $\Psi = \Psi_{(x_0,r)}$ such that by setting $\tilde{\Omega} := \Psi(B(x_0, r))$, we have

$$\Psi(\mathcal{H} \cap B(x_0, r)) = \{x_N = 0\} \cap \tilde{\Omega}.$$ 

We denote this assumption by $(H_\Omega^v)$.

**Theorem 4.1.** Assume $(H_\Omega^v)$ and $(H_C)$. If $u$ and $v$ are respectively a bounded usc subsolution and a bounded lsc supersolution of $w_t + \mathbb{H}^-(x,t,Dw) = 0$ in $Q(x_0,t_0)(r,h)$. Then

$$\|(u - v)\|_{L^\infty(Q(x_0,t_0)(r,h))} \leq \|(u - v)\|_{L^\infty(\partial_p Q(x_0,t_0)(r,h))}$$

(4.1)

**Proof.** We make the change of variable: $\tilde{u}(x,t) := u(\Psi^{-1}(x),t), \tilde{v}(x,t) := v(\Psi^{-1}(x),t)$. The functions $\tilde{u}, \tilde{v}$ are respectively sub and supersolution of (6.1) with $\tilde{Q} = \mathcal{\tilde{O}} \times (t_0 - h, t_0)$, for an Hamiltonian $\mathbb{H}^-$ associated to

$$\tilde{b}_i(x,t,\cdot) := D\Psi(\Psi^{-1}(x))b_i(\Psi^{-1}(x),t,\cdot), \tilde{l}_i(x,t,\cdot) := l_i(\Psi^{-1}(x),t,\cdot) \quad \text{for} \ x \in \mathcal{\tilde{O}}, \ t \in [t_0 - h, t_0].$$

These dynamics and costs satisfy $(H_C)$ for some new constants denoted by $\bar{M}_b, \bar{L}_b, \bar{M}_t, \bar{m}_t, \bar{\delta}$.

We apply Lemma 6.1 which gives (6.2) which is exactly the result we want by making the change back.

We now turn to one of our main results, which is the

**Theorem 4.2.** Assume $(H_\Omega)$ and $(H_C)$. Let $u$ be a bounded, Lipschitz continuous subsolution of $u_t + \mathbb{H}^-(x,t,Du) = 0$ in $\mathbb{R}^N \times (0,T)$ and $v$ be a bounded, lsc supersolution of $v_t + \mathbb{H}^-(x,t,Dv) = 0$ in $\mathbb{R}^N \times (0,T)$. If $u(x,0) \leq v(x,0)$ in $\mathbb{R}^N$, then $u \leq v$ in $\mathbb{R}^N \times (0,T)$.

**Proof of Theorem 4.2.** We first prove the

**Lemma 4.3.** For $K > 0$ large enough, $\psi(x,t) := -Kt - (1 + |x|^2)^{1/2}$ satisfies $\psi_t + \mathbb{H}^-(x,t,D\psi) \leq -1$.

**Proof.** We just estimate as follows:

$$\psi_t + \mathbb{H}^-(x,t,D\psi) \leq -K + M_b|D\psi| + M_t \leq -K + M_b + M_t .$$

Hence taking $K \geq M_b + M_t + 1$ yields the result.
Using the function $\psi$ of Lemma 4.3, we introduce, for $\mu \in (0,1)$ close to 1, the function $u_\mu(x,t) := \mu u(x,t) + (1-\mu)\psi(x,t)$. Because of the convexity properties of $H_1,H_2,H_T$, it satisfies $(u_\mu)_t + H^-(x,t,Du_\mu) \leq -(1-\mu)$. Then we consider

$$M_\mu := \sup_{\mathbb{R}^N \times [0,T]} (u_\mu(x,t) - v(x,t)).$$

Since $u_\mu(x,t) \to -\infty$ as $|x| \to \infty$ (uniformly with respect to $t \in [0,T]$) and $v$ is bounded, this “sup” is actually a “max” and it is achieved at $(x_0,t_0)$. Notice also that $M_\mu \to M := \sup_{\mathbb{R}^N \times [0,T]} (u(x,t) - v(x,t))$ as $\mu \to 1$. We argue by contradiction, assuming that $M > 0$, which implies that $M_\mu > 0$ for $\mu$ close enough to 1. From now on, we assume that we have chosen such a $\mu$ and therefore $M_\mu > 0$.

Next we remark that $t_0 > 0$ since $u_\mu(x,0) - v(x,0) \leq 0$ in $\mathbb{R}^N$ and we first treat the case when $x_0 \in \mathcal{H}$. In that way, since $(\mathbf{H}_\Omega)$ holds, we can choose $r > 0$, small enough in order that $(\mathbf{H}_{x_0})$ holds. On the other hand, we choose any $h$ such that $t_0 - h \geq 0$, say $h = t_0$.

The next step consists in introducing the function

$$\bar{u}_\mu(x,t) := u_\mu(x,t) + (1-\mu)^2\left(t - t_0 - |x-x_0|^2\right).$$

We claim that $\bar{u}_\mu$ is a subsolution of $(\bar{u}_\mu)_t + H^-(x,t,D\bar{u}_\mu) = 0$ for $\mu$ close enough to 1. Indeed, a direct computation gives

$$(\bar{u}_\mu)_t + H^-(x,\bar{u}_\mu,D\bar{u}_\mu) \leq (u_\mu)_t + H^-(x,u_\mu,Du_\mu) + (1-\mu)^2\{1 + 2M_\mu r\}$$

$$\leq -(1-\mu) + (1-\mu)^2\{1 + 2M_\mu r\} \leq 0$$

for $\mu$ sufficiently close to 1.

Thus, we use Theorem 4.1 with the pair of sub/supersolution $(\bar{u}_\mu,v)$ and we obtain in particular

$$M_\mu = u_\mu(x_0,t_0) - v(x_0,t_0) = \bar{u}_\mu(x_0,t_0) - v(x_0,t_0) \leq \|\bar{u}_\mu - v\|_{L^\infty(\partial B(x_0,t_0) \times (r_0,t_0))}. $$

However, on the parabolic boundary $|\bar{u}_\mu - v| < M_\mu$. Indeed, on $\partial B(x,r) \times (t_0 - h,t_0)$, we have

$$\bar{u}_\mu(x,t) - v(x,t) = u_\mu(x,t) - v(x,t) + (1-\mu)^2\left(t - t_0 - r^2\right) \leq M_\mu - (1-\mu)^2 r^2,$$

while on $B(x_0,r) \times \{t_0 - h\}$,

$$\bar{u}_\mu(x,t) - v(x,t) = u_\mu(x,t) - v(x,t) + (1-\mu)^2\left(t - t_0 - |x-x_0|^2\right) \leq M_\mu - (1-\mu)^2 h.$$

This gives a contradiction.

We can argue in the same way if $x_0 \in \Omega_1$ or $x_0 \in \Omega_2$ : in fact this is even easier since we may choose $r$ such that either $\overline{B}(x_0,r) \subset \Omega_1$ or $\overline{B}(x_0,r) \subset \Omega_2$; with this choice we only deal with classical Hamilton-Jacobi Equations without discontinuities and we have just to apply classical results.

The contradiction shows that $M \leq 0$ and the proof is complete.

As a consequence, we have the following
Theorem 4.4. Assume \((H_3), (H_4)\) and \((H_C)\). Then

(i) The value function \(U^-\) is continuous and the unique solution of

\[
\begin{align*}
  u_t + \mathbb{H}^-(x, t, Du) &= 0 \text{ in } \mathbb{R}^N \times (0, T) , \\
  u(x, 0) &= g(x) \text{ in } \mathbb{R}^N .
\end{align*}
\]

(ii) \(U^-\) is the minimal supersolution of \((1.3)-(1.5)-(1.6)-(4.3)\) and \(U^+\) is the maximal subsolution of \((1.3)-(1.5)-(1.6)-(4.3)\).

Proof. The proof of (i) is a direct consequence of Theorem 3.3 and 4.2: indeed \((U^-)^*\) and \((U^-)_*\) are respectively sub and supersolution of \((1.2)\) by Theorem 3.3 and since \((U^-)^*(x, 0) = (U^-)_*(x, 0) = g(x)\) in \(\mathbb{R}^N\), Theorem 4.2 implies that \((U^-)^* \leq (U^-)_*\) in \(\mathbb{R}^N \times [0, T]\), which implies that \(U^-\) is continuous because \((U^-)_*\) satisfies \((U^-)^*\) in \(\mathbb{R}^N \times [0, T]\) and therefore \((U^-)_* = U^- = (U^-)^*\) in \(\mathbb{R}^N \times [0, T]\). As a consequence \(U^-\) being both upper and lower semicontinuous, it is continuous. The uniqueness is a direct consequence of Theorem 4.2.

For (ii), the first part is also a direct consequence of Theorem 4.2 since any supersolution of \((1.3)-(1.5)-(1.6)-(4.3)\) is a supersolution of \((4.2)-(4.3)\).

Finally, for \(U^+\), we follow the same idea as for \(U^-\) above and of [6] : if \(u\) is a subsolution of \((1.3)-(1.5)-(1.6)-(4.3)\), then by Theorem 3.7 it satisfies

\[
u_t + H_T^\text{res}(x, t, Du) \leq 0 \quad \text{on } \mathcal{H},
\]

and in order to compare it with the supersolution \((U^+)_*\), we use Theorem 3.5 (instead of Theorem 3.9 for the supersolutions in the case of \(\mathbb{H}^-\)) together with the regularization of the appendix (done on \(\mathbb{H}^+\) and not \(\mathbb{H}^-\)). We skip the details since it is a straightforward adaptation of the proof of Theorems 4.1-4.2.

Notice that, as a consequence, we have \((U^+)^* \leq (U^+)_*\) in \(\mathbb{R}^N \times [0, T]\) since \((U^+)^*\) is a subsolution of \((1.3)-(1.5)-(1.6)-(4.3)\), which implies the continuity of \(U^+\).

Remark 4.5. We emphasize the key role of Theorem 3.3: \(U^+\) is the only supersolution of the \(\mathbb{H}^-\) equation for which we have such a property and this is why we do not have a complete comparison result for this equation (contrary to the \(\mathbb{H}^-\) one).

\[\Box\]

5 Stability

In this section we prove stability results when we have a sequence of dynamics and costs \(b_i^\varepsilon, l_i^\varepsilon, g^\varepsilon\) converging locally uniformly. Let us begin with a standard stability result for sub/super solutions.

Theorem 5.1. Assume \((H_3)\) and that, for all \(\varepsilon > 0\), \(b_i^\varepsilon, b_2^\varepsilon, l_i^\varepsilon, l_2^\varepsilon\) satisfy \((H_4^\varepsilon)-(H_5^\varepsilon)\) with constants uniform in \(\varepsilon\). Let \(H^\varepsilon_i\) \((i = 1, 2)\) and \(H_T^\varepsilon\) be defined as in \((1.3)\) and \((3.1)\) respectively with these dynamics and costs. If

\[
(b_1^\varepsilon, b_2^\varepsilon, l_1^\varepsilon, l_2^\varepsilon) \to (b_1, b_2, l_1, l_2) \text{ locally uniformly in } \mathbb{R}^N \times [0, T] \times A ,
\]

\[
g^\varepsilon \to g \text{ locally uniformly in } \mathbb{R}^N ,
\]

\[
\]
Lemma 5.2. Under the assumptions of Theorem 5.1 (ii), easily that there exists a sequence \( (\psi, \psi) \) that \( \psi \) thanks to (H) then the following holds

By the definition of \( \limsup \) that \( K \)

The only case that need to be detailed is the proof of (ii) and more precisely \( \bar{u} \) fulfilling the inequality \( u_t + H_T(x, 0, Du) \leq 0 \) on \( \mathcal{H} \). To do so, we use the

Lemma 5.2. Under the assumptions of Theorem 5.1 (ii), \( H_T \) converges to \( H_T \) locally uniformly.

We postpone the proof and return to the proof of Theorem 5.1 (ii). We first remark that, thanks to (H), we can argue as in the proof of uniqueness and suppose that we are working with \( \mathcal{H} = \{ x_N = 0 \} \) (see assumption (H) and its consequences).

If \( \phi \in C^1(\mathcal{H} \times [0, T]) \) and if \( (x'_0, 0, t_0) \) is a strict local maximum point of \( \bar{u}(y', 0, s) - \phi(y', s) \) in \( \mathcal{H} \times [0, T] \), our aim is to prove that

\[
\phi_t(x'_0, 0) + H_T((x'_0, 0), 0, D\phi(x'_0, 0)) \leq 0.
\]

By the definition of \( \limsup u \), there exists a sequence \( (\bar{x}_\varepsilon, \bar{t}_\varepsilon) \) converging to \( (x'_0, 0, t_0) \) such that \( \bar{u}(x'_0, 0, t_0) = \lim_{\varepsilon \to 0} u(x_\varepsilon, t_\varepsilon) \). If \( (\bar{x}_\varepsilon)_N \neq 0 \), we set \( K_\varepsilon = |(\bar{x}_\varepsilon)_N|^{-1/2} \), otherwise \( K_\varepsilon = \varepsilon^{-1} \). Notice that \( K_\varepsilon \to +\infty \) as \( \varepsilon \to 0 \).

We consider the function \( \psi_\varepsilon(x, t) := u_\varepsilon(x, s) - \phi(x', s) - K_\varepsilon |x_N| \). By classical techniques, using that \( \psi_\varepsilon(\bar{x}_\varepsilon, \bar{t}_\varepsilon) \to \bar{u}(x', 0, t_0) - \phi(x', t_0) \) (this key property justifies the choice of \( K_\varepsilon \)), one proves easily that there exists a sequence \( (x_\varepsilon, t_\varepsilon) \) of maximum points of \( \psi_\varepsilon \) which converges to \( (x'_0, 0, t_0) \).
If \( x_\varepsilon \in \Omega_1 \subset \{ x \in \mathbb{R}^N : x_N > 0 \} \), \( x \mapsto |x_N| \) is smooth in a neighborhood of \( x_\varepsilon \) and, since \( u_\varepsilon \) is an usc subsolution of \( (5.1) \), we have
\[
\phi_t(x_\varepsilon', 0, t_\varepsilon) + H_1^\varepsilon(x_\varepsilon, t_\varepsilon, D_H\phi(x_\varepsilon', 0, t_\varepsilon) + K_\varepsilon e_N) \leq 0
\]
but, recalling that \( K_\varepsilon \to +\infty \) as \( \varepsilon \to 0 \), this inequality cannot hold for \( \varepsilon \) small enough because of \( (H_0^\varepsilon) \). To be more precise, since the \( b_i^\varepsilon \) converge locally uniformly to \( b_i \) which satisfy \( (H_0^\varepsilon) \), we can take a uniform \( \delta = \tilde{\delta} \) in Lemma 6.3 which proves the claim.

In the same way \( x_\varepsilon \) cannot be in \( \Omega_2 \). As a consequence, \( x_\varepsilon \) is on \( \mathcal{H} \) and is a maximum point of \( (y', s) \mapsto u_\varepsilon(y', 0, s) - \phi(y', s) \). But \( u_\varepsilon \) is an usc subsolution of \( (5.1) \), therefore the \( H_T^\varepsilon \)-inequality holds and we conclude in the classical way using Lemma 5.2.

Now we prove Lemma 5.2. By the definition of \( H_T^\varepsilon \),
\[
H_T^\varepsilon(x, t, p) := \sup_{A_0(x, t)} \{ -\langle b_H^\varepsilon(x, t, a), p \rangle - l_H^\varepsilon(x, t, a) \}.
\]
If \( x \in \mathcal{H}, t \in (0, T) \) and if \( (x_\varepsilon, t_\varepsilon) \in \mathcal{H} \times (0, T) \) converging to \( (x, t) \) and if \( p_\varepsilon \to p \), we use this definition to write
\[
H_T^\varepsilon(x_\varepsilon, t_\varepsilon, p_\varepsilon) = -\langle b_H^\varepsilon(x_\varepsilon, t_\varepsilon, a_\varepsilon), p_\varepsilon \rangle - l_H^\varepsilon(x_\varepsilon, t_\varepsilon, a_\varepsilon) \geq -\langle b_H^\varepsilon(x_\varepsilon, t_\varepsilon, a), p_\varepsilon \rangle - l_H^\varepsilon(x_\varepsilon, t_\varepsilon, a) \tag{5.4}
\]
for any \( a \in A_0(x_\varepsilon, t_\varepsilon) \).

Again by definition, we have
\[
b_H^\varepsilon(x_\varepsilon, t_\varepsilon, a_\varepsilon) = \mu_\varepsilon b_1(x_\varepsilon, t_\varepsilon, a_1^\varepsilon) + (1 - \mu_\varepsilon) b_2(x_\varepsilon, t_\varepsilon, a_2^\varepsilon),
\]
and extracting subsequences, we can assume that \( b_H^\varepsilon(x_\varepsilon, t_\varepsilon, a_\varepsilon) \) converges to \( b_H(x, t, \bar{a}) \). In the same way, \( l_H^\varepsilon(x_\varepsilon, t_\varepsilon, a) \to l_H(x, t, \bar{a}) \). It remains to show that
\[
H_T(x, t, p) = -\langle b_H(x, t, \bar{a}), p \rangle - l_H(x, t, \bar{a})
\]
This can be done using Inequality \( (5.4) \) and the arguments of Lemma 6.5: if
\[
H_T(x, t, p) = -\langle b_H(x, t, \bar{a}), p \rangle - l_H(x, t, \bar{a}),
\]
we can build a sequence \( \bar{a}_\varepsilon \in A_0(x_\varepsilon, t_\varepsilon) \) such that
\[
-\langle b_H^\varepsilon(x_\varepsilon, t_\varepsilon, \bar{a}_\varepsilon), p_\varepsilon \rangle - l_H^\varepsilon(x_\varepsilon, t_\varepsilon, \bar{a}_\varepsilon) \to -\langle b_H(x, t, \bar{a}), p \rangle - l_H(x, t, \bar{a}).
\]
Passing to the limit in the inequality \( (5.4) \) with \( a = \bar{a}_\varepsilon \), we have the desired conclusion.

We now turn to the stability of the minimal and maximal solutions. To do so, we denote by \( \mathcal{T}_{x,t}^\varepsilon \) [resp. \( \mathcal{T}_{x,t}^{reg,\varepsilon} \)] the set of admissible [resp. admissible and regular] trajectories associated to the dynamics \( b_i^\varepsilon \), \( i = 1, 2 \). We also define the costs functionals \( J^\varepsilon \) as in \( (2.5) \), but with \( \ell^\varepsilon \) and \( g^\varepsilon \).

**Lemma 5.3.** Under the assumptions of Theorem 5.1, if for any \( \varepsilon > 0 \), \( (X^\varepsilon, a^\varepsilon) \in \mathcal{T}_{x,t}^\varepsilon \), the following holds
i) There exists a subsequence \((X_{\varepsilon_n}^\varepsilon, a_{\varepsilon_n})\), converging to an admissible trajectory \((X, a) \in \mathcal{T}_{x,t}\). More precisely, \(X_{\varepsilon_n}^\varepsilon \to X\) uniformly in \([0,T]\) and
\[
J(x, t; (X_{\varepsilon_n}^\varepsilon, a_{\varepsilon_n})) \to J(x, t; (X, a)) \quad \text{uniformly in} \ [0,T].
\]

ii) If, moreover, \((X_{\varepsilon}, a_{\varepsilon}) \in \mathcal{T}_{x,t}^{\text{reg,}\varepsilon}\) for any \(\varepsilon > 0\) (i.e., the trajectories are regular), then we have a subsequence for which the limit trajectory is also regular: \((X, a) \in \mathcal{T}_{x,t}^{\text{reg}}\).

iii) The results in i) (and ii) ) hold true also if we assume that for each \(\varepsilon > 0\), the trajectories \((X_{\varepsilon}, a_{\varepsilon}) \in \mathcal{T}_{x,t}^{\varepsilon}\) of the mixed variable \((X, a, \varepsilon) \in \mathcal{T}_{x,t}^{\varepsilon}\), and we assume that \((x_{\varepsilon}, t_{\varepsilon}) \to (x, t)\) as \(\varepsilon \to 0\).

**Proof.** The proof of i) is almost standard and we only provide it for the reader’s convenience. On the contrary, the proof of ii) reveals unexpected difficulties (but which come from the particular features of the control problem).

**Proof of i) —** Since we want to pass to the limit both on the dynamic and the cost, we rewrite the differential inclusion in a different way, taking into account both at the same time.

We fix \((x, t)\). Since the trajectories go backward in time, we introduce the variable \(\sigma(s) := t - s\), starting at \(\sigma(0) = t\). Then, for any \(\varepsilon > 0\), using the admissible trajectory \((X_{\varepsilon}, a_{\varepsilon})\) we set
\[
Y_{\varepsilon}(s) := \int_{0}^{s} \ell_{\varepsilon}(X_{\varepsilon}(\tau), \sigma(\tau), a_{\varepsilon}(\tau)) \, d\tau
\]
where the Lagrangian \(\ell_{\varepsilon}\) is defined as in (2.6), but with \(l_{1,\varepsilon}^i, l_{2,\varepsilon}^i\). In order to take into account both \(X_{\varepsilon}\) and \(Y_{\varepsilon}\) at the same time and the function \(\sigma(\cdot)\), we consider the mixed variable \(Z := (X, Y, \sigma) \in \mathbb{R}^N \times \mathbb{R} \times [0,T]\), and translate the differential inclusion in terms of \(Z\).

To do so, we use \((H_{3,\varepsilon})\) and introduce, for \(i = 1, 2\), the sets
\[
\text{BL}_{i}(Z) := \{(b_{i}^\varepsilon(X, \sigma, \alpha_i), l_{i}^\varepsilon(X, \sigma, \alpha_i), -1) : \alpha_i \in A_i \},
\]
\[
\text{BL}^\varepsilon(Z) := \begin{cases} 
\text{BL}_{i}(Z) & \text{if } X \in \Omega_i, \\
\overline{\text{co}}(\text{BL}_{1}(Z) \cup \text{BL}_{2}(Z)) & \text{if } X \in \mathcal{H}.
\end{cases}
\]

It turns out that the triple \(Z := (X_{\varepsilon}, Y_{\varepsilon}, \sigma)\) is a solution of the differential inclusion
\[
\dot{Z}(s) \in \text{BL}^\varepsilon(Z(s)) \quad \text{for a.e. } s \in [0,t), \quad \text{with } Z(0) = (x,0,t).
\]

We first notice that since the \(b_{i}^\varepsilon, l_{i}^\varepsilon\) are uniformly bounded, the \(Z_{\varepsilon}\) are equi-Lipschitz and equi-bounded on \([0,T]\). Therefore we can extract a subsequence (denoted by \(Z_{\varepsilon,n}\)) which converges uniformly on \([0,T]\) to some \(Z = (X, Y, \sigma)\). Moreover, for any given \(\delta > 0\) and for \(\varepsilon > 0\) small enough, we have, for any \(s \in (0,t)\)
\[
\text{BL}^\varepsilon(Z_{\varepsilon,n}) \subset \text{BL}^\varepsilon(Z) + \delta B_{N+2},
\]
where \(B_{N+2}\) is the unit ball in \(\mathbb{R}^{N+2}\), centered at the origin. Using this information, it is immediate that \(\dot{Z}(s) \in \text{BL}^\varepsilon(Z(s))\). In particular the limit trajectory is admissible: there exists a control \(a(\cdot)\) such that \((X, a) \in \mathcal{T}_{x,t}\). (See Filippov’s Lemma [1, Theorem 8.2.1] or the proof of Theorem 2.1 in [6]).
Finally, since \( g^\varepsilon \to g \) locally uniformly in \( \mathbb{R}^N \) and \( X^{\varepsilon_n} \to X \) uniformly on \([0, T]\), we deduce that \( J(x, t; (X^{\varepsilon_n}, a^{\varepsilon_n})) \) converges to \( J(x, t; (X, a)) \) uniformly with respect to \( t \in [0, T] \).

**Proof of ii)** — The difficulty comes from two facts: the first one is that we have to deal with weak convergences in the \( b^\varepsilon_i, b^\varepsilon_H \)-terms but the problem is increased by the fact that some pieces of the trajectory \( X(\cdot) \) on \( \mathcal{H} \) can be obtained as limits of trajectories \( X^\varepsilon(\cdot) \) which lie either on \( \mathcal{H}, \Omega_1 \) or \( \Omega_2 \). In other words, the indicator functions \( \mathbb{1}_{\{X \in \mathcal{H}\}}(\cdot) \) do not converge to \( \mathbb{1}_{\{X \in \mathcal{H}\}}(\cdot) \), and similarly the \( \mathbb{1}_{\{X \in \Omega_1\}}(\cdot) \) do not converge to \( \mathbb{1}_{\{X \in \Omega_1\}}(\cdot) \). We proceed in three steps.

**Step 1.** We first recall that

\[
\dot{X}^\varepsilon(s) = \sum_{i=1,2} b_i^\varepsilon(X^\varepsilon(s), \sigma(s), \alpha_i^\varepsilon(s)) \mathbb{1}_{\{X^\varepsilon \in \Omega_i\}}(s) + b_H^\varepsilon(X^\varepsilon(s), \sigma(s), a^\varepsilon(s)) \mathbb{1}_{\{X^\varepsilon \in \mathcal{H}\}}(s)
\]

converges weakly (i.e. in \( L^\infty(0, T) \) weak–∗) to

\[
\dot{X}(s) = \sum_{i=1,2} b_i(X(s), \sigma(s), \alpha_i(s)) \mathbb{1}_{\{X \in \Omega_i\}}(s) + b_H(X(s), \sigma(s), a(s)) \mathbb{1}_{\{X \in \mathcal{H}\}}(s),
\]

for some control \( a(\cdot) \) such that \( (X, a) \in T_{x,t} \). This weak convergence does not create any difficulty if \( X(s) \) is in \( \Omega_i \) for \( i = 1, 2 \) but it is a little bit more complicated if \( X(s) \in \mathcal{H} \) since the term \( b_H(X(s), \sigma(s), a(s)) \mathbb{1}_{\{X \in \mathcal{H}\}}(s) \) is a weak limit of

\[
\sum_{i=1,2} b_i^\varepsilon(X^\varepsilon(s), \sigma(s), \alpha_i^\varepsilon(s)) \mathbb{1}_{\{X^\varepsilon \in \Omega_i\}}(s) \mathbb{1}_{\{X^\varepsilon \in \mathcal{H}\}}(s) + b_H^\varepsilon(X^\varepsilon(s), \sigma(s), a^\varepsilon(s)) \mathbb{1}_{\{X^\varepsilon \in \mathcal{H}\}}(s) \mathbb{1}_{\{X \in \mathcal{H}\}}(s),
\]

and we have to check that both terms cannot generate singular strategies. In order to examine carefully the mechanism of the weak convergence on \( \mathcal{H} \), we write, for \( 0 \leq \tau \leq t \)

\[
X^\varepsilon(\tau) - x = \sum_{i=1,2} \int_0^\tau b_i^\varepsilon(X^\varepsilon(s), \sigma(s), \alpha_i^\varepsilon(s)) \mathbb{1}_{\{X^\varepsilon \in \Omega_i\}}(s) ds + \int_0^\tau b_H^\varepsilon(X^\varepsilon(s), \sigma(s), a^\varepsilon(s)) \mathbb{1}_{\{X^\varepsilon \in \mathcal{H}\}}(s) ds,
\]

and we use a slight modification of the procedure leading to relaxed control as follows. We write

\[
\int_0^\tau b_i^\varepsilon(X^\varepsilon(s), \sigma(s), \alpha_i^\varepsilon(s)) \mathbb{1}_{\{X^\varepsilon \in \Omega_i\}}(s) ds = \int_0^\tau \int_{A_1} b_i^\varepsilon(X^\varepsilon(s), \sigma(s), \alpha_1) \nu_i^\varepsilon(s, d\alpha_1) ds,
\]

where \( \nu_i^\varepsilon(s, \cdot) \) stands for the measure defined on \( A_1 \) by \( \nu_i^\varepsilon(s, E) = \delta_{\alpha_i^\varepsilon}(E) \mathbb{1}_{\{X^\varepsilon \in \Omega_i\}}(s) \), for any Borelian set \( E \subset A_1 \). Similarly we define \( \nu_2^\varepsilon \) and \( \nu_H^\varepsilon \) for the other terms. Notice that \( \nu_H^\varepsilon \) is a bit more complex measure since it concerns controls of the form \( a = (\alpha_1, \alpha_2, \mu) \) on \( A \), but it works as for \( \nu_1 \) so we omit the details.

These measures are uniformly bounded in \( \varepsilon \) since they all have a total mass less than (or equal to) one. Hence, up to successive extractions they all converge weakly to some measures \( \nu_1, \nu_2, \nu_H \).

Since the total mass is \( \nu_1^\varepsilon + \nu_2^\varepsilon + \nu_H^\varepsilon = 1 \), we obtain in the limit \( \nu_1 + \nu_2 + \nu_H = 1 \). Using that (also
up to extraction from the proof of i) above), $X^\varepsilon$ converges uniformly on $[0,t]$ and the local uniform convergence of the $b_i^\varepsilon$, we get that

$$
\int_{A_1} b_i^\varepsilon(X^\varepsilon(s), \sigma(s), \alpha_1) \nu_i^\varepsilon(s, d\alpha_1) \to \int_{A_1} b_i(X(s), \sigma(s), \alpha_1) \nu_1(s, d\alpha_1), \text{ weakly in } L^\infty(0,T).
$$

Introducing $\pi_1(s) := \int_{A_1} \nu_1(s, d\alpha_1)$ and using the convexity of $A_1$ together with measurable selection argument (see [1, Theorem 8.1.3]), the last integral can be written as $b_1(X(s), \sigma(s), \alpha_1^\varepsilon(s))\pi_1(s)$ for some control $\alpha_1^\varepsilon \in L^\infty(0,T; A_1)$. The same procedure for the other two terms provides the controls $\alpha_2^\varepsilon(\cdot), a^\varepsilon(\cdot)$ and functions $\pi_2(\cdot), \pi_H(\cdot)$. In principle, those controls can be different from $\alpha_1(\cdot), \alpha_2(\cdot)$ and $a(\cdot)$ but this will not be a problem since $\alpha_1^\varepsilon(\cdot), \alpha_2^\varepsilon(\cdot), a^\varepsilon(\cdot)$ are just intermediate controls which are used to prove that the strategy $a(\cdot)$ is regular.

**Step 2.** We then deal with the $b_i$-terms. If $d_{\Omega_i}(x)$ denotes the distance from $x$ to $\Omega_i$ then $d_{\Omega_i}(X^\varepsilon)$ is a sequence of Lipschitz continuous functions which converges uniformly to $d_{\Omega_i}(X)$ and, up to an additional extraction of subsequence, we may assume that the derivatives converges weakly in $L^\infty$ (weak-$*$ convergence). As a consequence, $\frac{d}{ds}[d_{\Omega_i}(X^\varepsilon)]\mathbf{1}_{\{X \in \mathcal{H}\}}$ converges weakly to $\frac{d}{ds}[d_{\Omega_i}(X)]\mathbf{1}_{\{X \in \mathcal{H}\}}$.

In order to use this convergence we have to compute $\frac{d}{ds}[d_{\Omega_i}(X^\varepsilon)]$. Using the extension of $n_i$ outside $\mathcal{H}$ in such a way that $Dd_{\Omega_i}(x) = -n_i(x)\mathbf{1}_{\{x \in \Omega_i\}}$, together with the regularity of $\Omega_i$ and Stampacchia’s Theorem we have

$$
\frac{d}{ds}[d_{\Omega_i}(X^\varepsilon)] = \dot{X}^\varepsilon(s) \cdot n_i(X^\varepsilon(s))\mathbf{1}_{\{X^\varepsilon \in \Omega_i\}}(s) \text{ for almost all } s \in (0,T).
$$

Indeed, on one hand, the distance function is regular outside $\mathcal{H}$ while, on the other hand, $\dot{X}^\varepsilon(s) \cdot n_i(X^\varepsilon(s)) = 0$ a.e. on $\mathcal{H}$. Therefore the above convergence reads, for $i \neq j$,

$$
\dot{X}^\varepsilon(s) \cdot n_i(X^\varepsilon(s))\mathbf{1}_{\{X^\varepsilon \in \Omega_j\}}(s)\mathbf{1}_{\{X \in \mathcal{H}\}}(s) \to \dot{X}(s) \cdot n_i(X(s))\mathbf{1}_{\{X \in \Omega_j\}}(s)\mathbf{1}_{\{X \in \mathcal{H}\}}(s) = 0
$$

in $L^\infty(0,T)$ weak-$*$, or equivalently using the above expression of $\dot{X}^\varepsilon(s)$,

$$
b_i^\varepsilon(X^\varepsilon(s), \sigma(s), \alpha_i^\varepsilon(s)) \cdot n_i(X^\varepsilon(s))\mathbf{1}_{\{X^\varepsilon \in \Omega_j\}}(s)\mathbf{1}_{\{X \in \mathcal{H}\}}(s) \to 0 \text{ in } L^\infty(0,T) \text{ weak-$*$}.
$$

This implies that for $i = 1,2$

$$
b_i(X(s), \sigma(s), \alpha_i^\varepsilon(s)) \cdot n_i(X(s)) \pi_i(s) = 0 \text{ a.e. on } \{X(s) \in \mathcal{H}\}, \quad (5.6)
$$

which means that, in these terms, the involved dynamics are regular since they are tangential (provided we take the $\alpha_i^\varepsilon$ as controls).

**Step 3.** We are now ready to prove that $(X,a) \in T_{x,t}^{\text{reg}}$, i.e. the dynamic in the $b_H$-term of (5.5) is regular. To do so, we introduce the convex set of regular dynamics for $z \in \mathcal{H}$ and $0 \leq s \leq t$ that we denote by

$$
K(z,s) := \{b_H(z,s,a_s), a_s \in A_{0}^{\text{reg}}(z,s)\} \subset \mathbb{R}^N.
$$

We notice that, for any $z \in \mathcal{H}$ and $s \in [0,T]$, $K(z,s)$ is closed and convex, and the mapping $(z,s) \mapsto K(z,s)$ is continuous on $\mathcal{H}$ for the Hausdorff distance. Then, for any $\eta > 0$, we consider
the subset of \([0,t]\) consisting of all times for which one has singular (\(\eta\)-enough) dynamics for the control \(a(\cdot)\), namely
\[
E^\eta_{\text{sing}} := \left\{ s \in [0,t] : X(s) \in \mathcal{H} \text{ and } \text{dist} \left( b_{\mathcal{H}}(X(s), t-s, a(s)); K(X(s), t-s) \right) \geq \eta \right\}
\]
and we argue by contradiction, assuming that, for some \(\eta > 0\), \(|E^\eta_{\text{sing}}| > 0\).

If we take \(s \in E^\eta_{\text{sing}}\), since \(K(X(s), t-s)\) is closed and convex, there exists an hyperplane separating \(b_{\mathcal{H}}(X(s), t-s, a(s))\) from \(K(X(s), t-s)\) and we may construct an affine function \(\Psi_s : \mathbb{R}^N \to \mathbb{R}\) of the form \(\Psi_s(z) = c(s) \cdot z + d(s)\) such that
\[
\Psi_s \left( b_{\mathcal{H}}(X(s), t-s, a(s)) \right) \leq -1 \text{ if } s \in E^\eta_{\text{sing}}, \quad \Psi_s \geq +1 \text{ on } K(X(s), t-s).
\]
Since the mapping \(s \mapsto b_{\mathcal{H}}(X(s), t-s, a(s))\) is measurable and \(s \mapsto K(X(s), t-s)\) is continuous (this can be seen as a consequence of Remark 6.7), we can assume that the coefficients \(c(s), d(s)\) are in \(L^\infty\) (they are bounded because the distance \(\eta > 0\) is fixed). Hence we may consider the integral
\[
I^\varepsilon := \int_0^t \left( \Psi_s(\dot{X}^\varepsilon(s)) \right) 1_{E^\eta_{\text{sing}}}(s) \, ds.
\]
On the one hand, since \(\Psi_s\) is an affine function, by weak convergence of \(\dot{X}^\varepsilon\) as \(\varepsilon \to 0\) and the fact that \(\dot{X} = b_{\mathcal{H}}\) when \(s \in E^\eta_{\text{sing}}\), we have
\[
I^\varepsilon \to \int_0^t \Psi_s(\dot{X}(s)) 1_{E^\eta_{\text{sing}}}(s) \, ds = \int_0^t \Psi_s \left( b_{\mathcal{H}}(X(s), t-s, a(s)) \right) 1_{E^\eta_{\text{sing}}}(s) \, ds \leq -|E^\eta_{\text{sing}}| < 0.
\]
On the other hand, we can also use the decomposition
\[
I^\varepsilon = \int_0^t c(s) 1_{E^\eta_{\text{sing}}}(s) \left( \sum_{i=1,2} b^\varepsilon_i(X^\varepsilon(s), t-s, a^\varepsilon_i(s)) 1_{\{X^\varepsilon \in \Omega_i\}}(s) \right) \, ds \tag{5.7}
\]
\[
+ \int_0^t c(s) 1_{E^\eta_{\text{sing}}}(s) b^\varepsilon_{\mathcal{H}}(X^\varepsilon(s), t-s, a^\varepsilon(s)) 1_{\{X^\varepsilon \in \mathcal{H}\}}(s) \, ds + \int_0^t d(s) 1_{E^\eta_{\text{sing}}}(s) \, ds.
\]
Notice that, in the second term above, \(a^\varepsilon(\cdot)\) is a regular control for the trajectory \(X^\varepsilon\), and we want to keep this property in the limit as \(\varepsilon \to 0\). To do so the key remark is the following: fix \(\varepsilon > 0\) and \(s \in [0,t]\) for each \(a^\varepsilon(s) \in A^\varepsilon_0(X^\varepsilon(s), t-s)\) there exists a \(\tilde{a}^\varepsilon(s) \in A^\varepsilon_0(X^\varepsilon(s), t-s)\) such that
\[
b^\varepsilon_{\mathcal{H}}(X^\varepsilon(s), t-s, a^\varepsilon(s)) - b^\varepsilon_{\mathcal{H}}(X^\varepsilon(s), t-s, \tilde{a}^\varepsilon(s)) = o_\varepsilon(1),
\]
where \(o_\varepsilon(1)\) represents any quantity which goes to zero as \(\varepsilon \to 0\). Indeed, for \(\varepsilon > 0\), we can apply Remark 6.7 for each \(s\) fixed and a measurable selection argument (see Filippov’s Lemma [11 Theorem 8.2.10]) to obtain the existence of the control \(a^\varepsilon(s) \in A^\varepsilon_0(X^\varepsilon(s), t-s)\) and then deduce the estimate by recalling that \(X^\varepsilon\) converges uniformly to \(X\). Moreover, by construction and using again a measurable selection argument (see Filippov’s Lemma [11 Theorem 8.2.10]), there exists a control \(a_\varepsilon(s) \in K(X(s), t-s)\) such that
\[
c(s)b_{\mathcal{H}}(X(s), t-s, a_\varepsilon(s)) = \min_{a \in K(X(s), t-s)} c(s)b_{\mathcal{H}}(X(s), t-s, a).
\]
Therefore, using the two above informations, we have
\[ \int_0^t \mathbb{1}_{E^\eta_{\text{sing}}} \langle s \rangle c(s) b_H^\varepsilon(X^\varepsilon(s), t-s, a^\varepsilon(s)) \mathbb{1}_{\{X^\varepsilon \in \mathcal{H}\}}(s) \, ds \geq \int_0^t \mathbb{1}_{E^\eta_{\text{sing}}} \langle s \rangle b_H(X(s), t-s, a_\ast(s)) \mathbb{1}_{\{X^\varepsilon \in \mathcal{H}\}}(s) \, ds + o_\varepsilon(1). \] (5.8)

Now we can pass to the weak limit in (5.7), (5.8) using the measures \( \nu_i \) and \( \nu_H \). We obtain
\[
\lim_{\varepsilon \to 0} I^\varepsilon \geq \int_0^t c(s) \mathbb{1}_{E^\eta_{\text{sing}}} \langle s \rangle \left( \sum_{i=1,2} \int_{A_i} b_i(X(s), t-s, \alpha_i(s)) \nu_i(s, \,d\alpha_i) + \int_{\mathcal{A}} b_H(X(s), t-s, a_\ast(s)) \nu_H(s, \,da) \right) \, ds
\]
\[
+ \int_0^t d(s) \mathbb{1}_{E^\eta_{\text{sing}}} \langle s \rangle \, ds
\]
\[
= \int_0^t \mathbb{1}_{E^\eta_{\text{sing}}} \langle s \rangle \Psi_s \left( \sum_{i=1,2} \int_{A_i} b_i(X(s), t-s, \alpha_i(s)) \nu_i(s, \,d\alpha_i) + \int_{\mathcal{A}} b_H(X(s), t-s, a_\ast(s)) \nu_H(s, \,da) \right) \, ds.
\]

Next we remark that, by (5.6), for \( i = 1, 2 \)
\[
\int_{A_i} b_i(X(s), t-s, \alpha_i(s)) \nu_i(s, \,d\alpha_i) = b_i(X(s), \sigma(s), \alpha_i^\ast(s)) \pi_i(s) \in K(X(s), t-s)
\]
and \( b_H(X(s), t-s, a_\ast(s)) \in K(X(s), t-s) \) by construction. Therefore, since \( \nu_1 + \nu_2 + \nu_H = 1 \) and \( K(X(s), t-s) \) is convex, we have
\[
\Psi_s \left( \sum_{i=1,2} \int_{A_i} b_i(X(s), t-s, \alpha_i(s)) \nu_i(s, \,d\alpha_i) + \int_{\mathcal{A}} b_H(X(s), t-s, a_\ast(s)) \nu_H(s, \,da) \right) \geq 1.
\]

We end up with \( \lim_{\varepsilon \to 0} I^\varepsilon \geq |E^\eta_{\text{sing}}| > 0 \) which is a contradiction with the fact that \( \lim I^\varepsilon = -|E^\eta_{\text{sing}}| < 0 \) by assumption. This proves that for any \( \eta > 0 \), \( |E^\eta_{\text{sing}}| = 0 \) and we deduce that for almost any \( s \), the limit dynamic \( b_H^\varepsilon(X(s), t-s, a(s)) \) is regular, which ends the proof.

**Proof of iii)** — This result follows by remarking that the arguments above holds true also is we consider a sequence \( (x^\varepsilon, t^\varepsilon) \to (x, t) \) as \( \varepsilon \to 0 \). We decided not to write it directly in the general case for the sake of simplicity.

**Remark 5.4.** Through the above proof, it can be easily seen that this stability result extends to the case when the domain depend on \( \varepsilon \) : indeed the proof is done using \( (H_\Omega) \), reducing to the case when \( \mathcal{H} = \{x_N = 0\} \) through Assumption \( (H_{\Omega}) \). To extend the result, we have to suppose that the \( \Omega_1^\varepsilon, \Omega_2^\varepsilon \) converges in a \( C^1 \)-sense to \( \Omega_1, \Omega_2 \) which means that the \( \Psi_s \) in \( (H_{\Omega}) \) have to converge in \( C^1 \). Note that, this convergence has to be assumed \( W^{2,\infty} \) if the required result is the convergence of solutions (instead of only sub or supersolution).

Finally, we have a stability result for the maximal and minimal solutions:

**Theorem 5.5.** Let us assume the hypotheses of Theorem 5.7. Then the associated value functions \( U^\varepsilon_- \) and \( U^\varepsilon_+ \) converge respectively to \( U^- \) and \( U^+ \).
Proof. Let us first remark that the convergence of $\mathbf{U}^-\varepsilon$ to $\mathbf{U}^-$ follows classically from the stability and comparison results Theorem 5.1 and Theorem 4.3. Moreover, the same results ensure us that $\mathbf{U}^+ \geq \limsup^* \mathbf{U}^+\varepsilon$. Indeed, we only now that $\mathbf{U}^+$ is the maximal subsolution of (5.2), therefore the stability can be applied only to the sub-solutions inequality.

In order to conclude we need to prove that $\mathbf{U}^+(x, t) \leq \liminf^* \mathbf{U}^+\varepsilon(x, t)$ for all $(x, t) \in \mathbb{R}^N \times [0, T]$. For each $\varepsilon > 0$, there exists a $(X^\varepsilon, a^\varepsilon) \in \mathcal{T}_{x, t}^{\text{reg}}$ such that

$$\mathbf{U}^+\varepsilon(x, t_\varepsilon) = J^\varepsilon(x, t_\varepsilon; (X^\varepsilon, a^\varepsilon))$$

and we first consider a subsequence $(X^{\varepsilon_n}, a^{\varepsilon_n})$ such that $\liminf U^+\varepsilon(x, t_\varepsilon) = \lim U^+_{\varepsilon_n}(x_{\varepsilon_n}, t_{\varepsilon_n})$. Then we use Lemma 5.3 parts iii): up to another extraction, we may assume that $U^+_{\varepsilon_n}(x_{\varepsilon_n}, t_{\varepsilon_n}) = J^{\varepsilon_n}(x_{\varepsilon_n}, t_{\varepsilon_n}; (X^{\varepsilon_n}, a^{\varepsilon_n})) \to J(x, t; (X, a))$ for some $(X, a) \in \mathcal{T}_{x, t}^{\text{reg}}$. Hence,

$$\liminf U^+\varepsilon(x, t_\varepsilon) = J(x, t; (X, a)) = \inf_{(X, a) \in \mathcal{T}_{x, t}^{\text{reg}}} J(x, t; (X, a)) = \mathbf{U}^+(x, t)$$

which ends the proof. 

6 Further Remarks and Extensions

The simplified (but relevant) framework we describe above can be extended in several directions and we start by remarks concerning the different regions $(\Omega_1, \Omega_2)$.

Because of the regularity assumptions we impose on the interfaces, there is no difference between $(\mathbf{H}_n)$ and using a possibly infinite number regular open subsets $(\Omega_i)_i$ with either $1 \leq i \leq K$ or $i \in \mathbb{N}$ and satisfying the following assumptions

$(\mathbf{H}_\Omega)$ For all $i \neq j$, $\Omega_i \cap \Omega_j = \emptyset$ and $\mathbb{R}^N = \bigcup_i \overline{\Omega_i}$; for any $z \in \Gamma := \mathbb{R}^N \setminus \left( \bigcup_i \Omega_i \right)$, there exist exactly two indices $i, j$ such that $z \in \overline{\Omega_i} \cap \overline{\Omega_j} := \Gamma_{\{i, j\}}$. Moreover $\Gamma := \bigcup_{i, j} \Gamma_{\{i, j\}}$ is $C^1$ in the controllable case and $W^{2, \infty}$ in the non-controllable case.

Concerning the regularity assumption on $\Gamma$, we point out that, since our key arguments are local, we are always in a two-domains framework and even in a two-mains framework with a flat interface. This is why we have chosen to present the paper with just two domains $\Omega_1$ and $\Omega_2$. On the other hand, this regularity is used through some change of variable and it is necessary in order that the transformed Hamiltonians satisfy the right assumptions to prove the comparison result. In the controllable case, the solutions are Lipschitz continuous and it could be enough to have continuous $b_i$’s and a $C^1$ change preserves this property. On the contrary, in the non-controllable case, the solutions may be just semi-continuous and the Lipschitz continuity of the $b_i$’s is necessary. Here we need a $W^{2, \infty}$ change to preserve this property.

Because of the same argument, the $\Omega_i$ may depend on $t$ and (this is an other way to formulate it) even we may assume that the $\Omega_i$ are domains in $\mathbb{R}^N \times (0, T)$ with the same regularity assumption as the one we use above (one has just to use $(\mathbf{H}_\Omega)$ with $\mathbb{R}^N$ being replaced by $\mathbb{R}^N \times (0, T)$). This is a consequence of the fact that, through our change of variable, $t$ and the tangential coordinates on $\Gamma$ play the same role. A corollary of this remark is that if $\mathbf{n}_i(\cdot) = (n_i^t, n_i^t_\perp) \in \mathbb{R}^N \times \mathbb{R}$ is the unit
normal vector pointing outwards defined on $\partial \Omega_i$, then we have to assume $n_i^T \neq 0$. This is required to avoid, for example, the pathological situation of $\Omega_i \subset \subset \mathbb{R}^N \times (0,T)$.

As far as the control problem is concerned, it is clear from the proof that we can take into account without any difficulty: (i) general discount factors $(c_i(x,t,\alpha_i))$, (ii) infinite horizon control problem with multiple domains in the non-controllable case (extending the results of [6]) and (iii) the case where one has an additional control problem on $\Gamma$ : here it suffices to check that the proof of Theorem 3.9 (of [6, Thm. 3.3]) extends to this case. To do so, we make two remarks

(a) The control problem on $\Gamma$ is associated to an Hamiltonian $G$ and (3.15) should be replaced by

$$\max(\phi_t(x,t) + H_T(x,t, D_H\phi(x,t)), \phi_t(x,t) + G(x,t, D_H\phi(x,t))) \geq 0.$$  

(b) The proof is going to consider (in the flat boundary case)

$$\varphi(\delta) := \max\{\phi_t(x,t) + H_1(x_0,v(x_0), D_H\phi(x_0') + \delta e_N), \phi_t(x,t) + H_2(x_0,v(x_0), D_H\phi(x_0') + \delta e_N),$$

$$\phi_t(x,t) + G(x,t, D_H\phi(x,t) + \delta e_N)\}$$

but $\phi_t(x,t) + G(x,t, D_H\phi(x,t) + \delta e_N) = \phi_t(x,t) + G(x,t, D_H\phi(x,t))$ since the $G$-Hamiltonian takes only into account the tangential part of the gradient and this quantity can be assumed to be strictly negative, otherwise we would be done. Therefore we see that the $G$-term plays no role in the proof.

To conclude, let us mention that the (interesting) cases of non-smooth $\Gamma$ where the different regions can be separated by triple junction or the case of chessboard situations are still (far) out of the scope of this article.

Appendix: the flat interface case

In this appendix, we assume that we are in a local “flat” situation. More precisely, we denote by $\tilde{\Omega}$ a bounded open subset of $\mathbb{R}^N$ (we actually have in mind the image of a ball $B(x,r)$ by a diffeomorphism $\psi$ which purpose is to flatten the interface). We assume that $0 \in \tilde{\Omega}$ and consider

$$\tilde{\Omega}_1 = \{x_N > 0\} \cap \tilde{\Omega}, \ \tilde{\Omega}_2 = \{x_N < 0\} \cap \tilde{\Omega}.$$  

We use the notations $\Gamma := \partial \tilde{\Omega}_1 \cap \partial \tilde{\Omega}_2 = \tilde{\Omega} \cap \{x_N = 0\}$, so that $\tilde{\Omega} = \tilde{\Omega}_1 \cup \tilde{\Omega}_2 \cup \Gamma$. Following Section 4 for $0 < h < t_0 < T$, we denote by $\tilde{Q} := \tilde{\Omega} \times (t_0 - h, t_0)$ and $\partial_p \tilde{Q} = \tilde{\Omega} \times \{t_0 - h\} \cup \partial \tilde{\Omega} \times (t_0 - h, t_0)$ its parabolic boundary. We also denote by $e_N$ the $N$-th unit vector in $\mathbb{R}^N$.

For $i = 1, 2$, we are given dynamics $\tilde{b}_i$ and costs $\tilde{\ell}_i$ in each $\tilde{\Omega}_i$ and we define $\tilde{H}_i$, $\tilde{H}_T$, $\tilde{H}_T^{reg}$ exactly as we did for the same Hamiltonians without the tilde. With the convention of Section 4 this allows us to consider the problem

$$\tilde{w}_t + \tilde{H}^-(x,t,D w) = 0 \quad \text{in } \tilde{Q}. \quad (6.1)$$

In all the following we assume that the dynamics and costs $\tilde{b}_i, \tilde{\ell}_i$ satisfy ($\mathbf{H}_C$) with constants denoted with a tilde: $\tilde{M}_b$, $\tilde{L}_b$, $\tilde{M}_t$, $\tilde{m}_t$ and $\tilde{\delta}$. Of course, this is the case after our reduction to the flat case if the $b_i$ and $l_i$ satisfy ($\mathbf{H}_C$).

We have the following comparison result for (6.1).
Lemma 6.1. Assume that the dynamics $\tilde{b}_i$ and costs $\tilde{l}_i$ satisfy $(H_C)$. If $\tilde{u}$ is an usc subsolution of (6.1) and $\tilde{v}$ a lsc supersolution of (6.1), then
\[
\| (\tilde{u} - \tilde{v})_+ \|_{L^\infty(\tilde{Q})} \leq \| (\tilde{u} - \tilde{v})_+ \|_{L^\infty(\partial_\nu \tilde{Q})}.
\] (6.2)

Proof. As in [6], the first steps consist in regularizing the subsolution. To do so, depending on the context, we write either $x$ or $(x', x_N)$ where $x' \in \mathbb{R}^{N-1}$ for a point in $\tilde{\Omega}$. Moreover, for the sake of simplicity, we will use both notations: $H(x, t, p)$ or $H(x', x_N, t, p)$.

STEP 1 — We first define the sup-conv in time and in the $x'$-variable for $\tilde{u}$ as follows
\[
\tilde{u}_\alpha (x, t) := \max_{y', z' \in Q} \left\{ \tilde{u}(y', x, t') - \exp(Kt) \left( \frac{|x' - y'|^2}{\alpha^2} + \frac{|t - t'|^2}{\alpha^2} \right) \right\}
\]
for some (large) positive constant $K$ to be chosen later. By the definition of the supremum, if it is achieved at $y', t'$, we have
\[
\tilde{u}(y', x, t') - \exp(Kt) \left( \frac{|x' - y'|^2}{\alpha^2} + \frac{|t - t'|^2}{\alpha^2} \right) = \tilde{u}(x, t),
\]
and therefore $\frac{|x' - y'|^2}{\alpha^2} + \frac{|t - t'|^2}{\alpha^2} \leq 2\|u\|_{\infty}$. Since we want to use viscosity inequalities for $u$ at $(y', x, t')$, we need these points to be in $\tilde{Q}$ and thanks to the above inequality, in order to do it, we have to restrict $(x, t)$ to be in
\[
\tilde{Q}_\alpha := \left\{ x \in \tilde{\Omega} : \text{dist}(x, \partial \tilde{\Omega}) > (2\|\tilde{u}\|_{\infty})^{1/2}\alpha \right\} \times \left( t_0 - h + (2\|\tilde{u}\|_{\infty})^{1/2}\alpha, t_0 - (2\|\tilde{u}\|_{\infty})^{1/2}\alpha \right).
\]

Our result on $\tilde{u}_\alpha$ is the

Lemma 6.2. The Lipschitz continuous function $\tilde{u}_\alpha$ satisfies $(\tilde{u}_\alpha)_+ + \tilde{H}^-(x, t, D\tilde{u}_\alpha) \leq m(\alpha)$ in $\tilde{Q}_\alpha$ for some $m(\alpha)$ converging to 0 as $\alpha$ tends to 0.

Proof. We first remark that $\tilde{u}_\alpha$ is Lipschitz continuous with respect to time $t$ and to the $x'$-variable by the classical properties of the sup-convolution. Moreover, it is Lipschitz continuous also with respect to the $x_N$-variable thanks to the coerciveness of the Hamiltonian (see also Lemma 6.3 below).

To check that it is a subsolution of the $\tilde{H}^-$-equation, we consider a test-function $\phi$ and a point $(x, t)$ where $\tilde{u}_\alpha - \phi$ reaches a local maximum. Then considering a maximum in $(z, s)$ of $\tilde{u}_\alpha(z, s) - \phi(z, s)$ leads us to consider a maximum in $(z, s, y', t')$ of $\tilde{u}(y', z_N, t') - \exp(Ks) \left( \frac{|z' - y'|^2}{\alpha^2} + \frac{|s - t'|^2}{\alpha^2} \right) - \phi(z, s)$. If
\[
\tilde{u}_\alpha(x, t) := \tilde{u}(y', x, t') - \exp(Kt) \left( \frac{|x' - y'|^2}{\alpha^2} + \frac{|t - t'|^2}{\alpha^2} \right),
\]
(we still write $y', t'$ for the variables where the max is attained for simplicity of notations) we deduce several things: first, we have a max in $z'$ and $s$ which gives
\[
D_{z'} \phi(x', x_N, t) = \frac{2(y' - x')}{\alpha^2} \exp(Kt),
\]
\[
\phi_t(x', x_N, t) = \frac{2(t' - t)}{\alpha^2} \exp(Kt) - K \exp(Kt) \left( \frac{|x' - y'|^2}{\alpha^2} + \frac{|t - t'|^2}{\alpha^2} \right).
\]
Then, if $x_N > 0$, we write down the viscosity inequality for $\tilde{u}$ and $\tilde{H}_1$, the proof being similar for $\tilde{H}_2$ if $x_N < 0$ and $\tilde{H}_T$ if $x_N = 0$ thanks to Lemma 6.5 below.

Using as test function $(y', x_N, t') \mapsto \phi(x', x_N, t') + \exp(Kt) \left( \frac{|x' - y'|^2}{\alpha^2} + \frac{|t - t'|^2}{\alpha^2} \right)$, we have

$$
\frac{2(t' - t)}{\alpha^2} \exp(Kt) + \tilde{H}_1 \left( y', x_N, t', \frac{2|y' - x'|}{\alpha^2} \exp(Kt) + \partial_{x_N} \phi(x', x_N, t') e_N \right) \leq 0.
$$

(6.3)

Notice that, combining the previous results, we have

$$
\phi_t(x, t) + K \exp(Kt) \left( \frac{|x' - y'|^2}{\alpha^2} + \frac{|t - t'|^2}{\alpha^2} \right) + \tilde{H}_1(y', x_N, t', D\phi) \leq 0.
$$

In order to obtain the right inequality, we have to change $y'$ in $x'$ and $t'$ in $t$. The only difficulty to do it, compared to the usual arguments, is the $\partial_{x_N} \phi(x', x_N, t')$-term in (6.3) which we need to control. This is done using the

**Lemma 6.3.** Assume that the dynamics $\tilde{b}_i$ and costs $\tilde{l}_i$ satisfy $(H_C)$. Then, there exists a constant $\tilde{C}_M$ such that, for $i = 1, 2$ and $p = (p', p_N)$, we have

$$
\tilde{H}_i(x, t, p) \geq \delta |p_N| - C_M(1 + |p'|),
$$

where $\delta$ is given by assumption $(H_{b_i}^1)$ and $\tilde{C}_M = \max\{\tilde{M}_b, \tilde{M}_l\}$ in $(H_{C}^1)$ and $(H_{C}^2)$.

We postpone the proof of Lemma 6.3 and conclude the proof of Lemma 6.2. Using the lemma for (6.3) yields

$$
|\partial_{x_N} \phi| \leq \delta^{-1} \left( \tilde{C}_M \left( \frac{|y' - x'|}{\alpha^2} \exp(Kt) + 1 \right) + \frac{2|t' - t|}{\alpha^2} \exp(Kt) \right).
$$

(6.4)

On the other hand, by the Lipschitz continuity of $\tilde{b}_1$ and the continuity of $\tilde{l}_1$, (in $(H_{C}^2)$) we have

$$
|\tilde{H}_1(y', x_N, t', p) - \tilde{H}_1(x, t, p)| \leq \tilde{L}_b(|y' - x'| + |t' - t|)|p| + \tilde{m}_l(|y' - x'| + |t' - t|).
$$

Hence $\phi_t(x, t) + \tilde{H}_1(x, t, D\phi) \leq r.h.s.,$ where

$$
r.h.s := -K \exp(Kt) \left( \frac{|x' - y'|^2}{\alpha^2} + \frac{|t - t'|^2}{\alpha^2} \right) + \tilde{L}_b(|y' - x'| + |t' - t|) \left( \frac{2|y' - x'|}{\alpha^2} \exp(Kt) + |\partial_{x_N} \phi| \right)
+ \tilde{m}_l(|y' - x'| + |t' - t|).
$$

Therefore, thanks to (6.4),

$$
r.h.s \leq -K \exp(Kt) \left( \frac{|x' - y'|^2}{\alpha^2} + \frac{|t - t'|^2}{\alpha^2} \right) + \tilde{L}_b \exp(Kt)(|y' - x'| + |t' - t|) \frac{2|y' - x'|}{\alpha^2}
+ \frac{\tilde{L}_b \exp(Kt)}{\delta}(|y' - x'| + |t' - t|) \left( \tilde{C}_M \frac{2|y' - x'|}{\alpha^2} + \frac{2|t' - t|}{\alpha^2} \right)
+ \frac{\tilde{L}_b \tilde{C}_M}{\delta}(|y' - x'| + |t' - t|) + \tilde{m}_b(|y' - x'| + |t' - t|).
$$
Since by construction $|y' - x'| + |t' - t| \leq 2(2||\tilde{u}||_\infty)^{1/2} \alpha$ the last line gives the $m(\alpha)$ which appears in the statement of Lemma 6.2. For the other terms, tedious but straightforward computations and the use of Cauchy-Schwarz inequality show that they give a negative contribution provided $K$ is big enough. And the proof of Lemma 6.2 is complete.

Now we turn to the proof of Lemma 6.3. We provide the proof in the case of $\tilde{H}_1$, it is similar for $\tilde{H}_2$. The (partial) controlability assumption ($H^0$) implies the existence of controls $\alpha_1, \alpha_2 \in A_1$ such that

$$-\tilde{b}_1(x, t, \alpha_1) \cdot e_N = \tilde{\delta} > 0, \ -\tilde{b}_1(x, t, \alpha_2) \cdot e_N = -\tilde{\delta}.$$ 

Now we compute $\tilde{H}_1(x, t, p)$ assuming that $p_N > 0$ (the other case is treated similarly).

$$\tilde{H}_1(x, t, p) \geq -\tilde{b}_1(x, t, \alpha_1) \cdot p - \tilde{l}_1(x, t, \alpha_1) \geq -\tilde{b}_1(x, t, \alpha_1) \cdot (p' + p_N e_N) - \tilde{l}_1(x, t, \alpha_1) \geq \tilde{\delta} p_N - \tilde{b}_1(x, t, \alpha_1) \cdot p' - \tilde{l}_1(x, t, \alpha_1) \geq \tilde{\delta} p_N - C_M |p'| - C_M,$$

the last line coming from the boundedness of $\tilde{b}_1$ and $\tilde{l}_1$. This concludes the proof.

**STEP 2** — We then define $\tilde{u}_\alpha^\varepsilon := \tilde{u}_\alpha \ast \rho_\varepsilon$ where $\rho_\varepsilon(x', t)$ is a standard (positive) mollifying kernel defined on $\mathbb{R}^{N-1} \times [0, T]$ as follows

$$\rho_\varepsilon(x', t) = \frac{1}{\varepsilon^{N-1}} \rho \left( \frac{x'}{\varepsilon}, \frac{t}{\varepsilon} \right),$$

where $\rho \in C^\infty(\mathbb{R}^{N-1} \times [0, T]), \int_{\mathbb{R}^{N-1} \times [0, T]} \rho(y) dy = 1, \text{ and } \text{supp}\{\rho\} = B_{\mathbb{R}^{N-1} \times [0, T]}(0, 1)$.

We assume that the support of $\rho_\varepsilon$ is the ball $B(0, \varepsilon)$ so that again, we define the convolution only in

$$\tilde{Q}_{\alpha, \varepsilon} := \{x \in \tilde{\Omega} : \text{dist}(x, \partial \tilde{\Omega}) > (2||\tilde{u}||_\infty)^{1/2} \alpha + \varepsilon \} \times (t_0 - h + (2||\tilde{u}||_\infty)^{1/2} \alpha + \varepsilon, t_0 - (2||\tilde{u}||_\infty)^{1/2} \alpha) \}.$$

**Lemma 6.4.** The function $v := \tilde{u}_\alpha^\varepsilon - m(\alpha) t$ satisfies $v_t + \tilde{H}_1(x, t, Dv) \leq 0$ in $\tilde{Q}_{\alpha, \varepsilon}$.

We skip the proof of this lemma which is analogous to the corresponding one in [6] since $\tilde{u}_\alpha$ is Lipschitz continuous.

**STEP 3** — We are now able to prove the comparison result for $\tilde{u}$ and $\tilde{v}$ in $\tilde{Q}$. At the level $(\alpha, \varepsilon)$ we have to argue in $\tilde{Q}_{\alpha, \varepsilon}$. First, we point out that for any $\eta > 0$, $\tilde{u}_\alpha^\varepsilon - \eta t$ is $C^1$ with respect to time $t$ and the $x_1, \ldots, x_{N-1}$ variables and therefore on $\Gamma \cap \tilde{Q}_{\alpha, \varepsilon}$ it is both a test-function for the $v$-inequality and it satisfies a strict subsolution inequality in the classical sense. Thanks to Theorem 3.9 we can argue as in [6] Theorem 4.1 and conclude that $v - (\tilde{u}_\alpha^\varepsilon - \eta t)$ cannot achieved a minimum point in $\Gamma \cap \tilde{Q}_{\alpha, \varepsilon}$. Moreover, since $\tilde{u}_\alpha^\varepsilon - \eta t$ is a strict subsolution, in $\tilde{\Omega}_1 \cap \tilde{Q}_{\alpha, \varepsilon}$ and $\tilde{\Omega}_2 \cap \tilde{Q}_{\alpha, \varepsilon}$ the conclusion follows by standard arguments. Thus $v - (\tilde{u}_\alpha^\varepsilon - \eta t)$ cannot achieve a minimum point in $\tilde{Q}_{\alpha, \varepsilon}$ and this immediately yields

$$||(\tilde{u}_\alpha^\varepsilon - \eta t - \tilde{v})|_{L^\infty(\tilde{Q}_{\alpha, \varepsilon})} \leq ||(\tilde{u}_\alpha^\varepsilon - \eta t - \tilde{v})|_{L^\infty(\partial \tilde{Q}_{\alpha, \varepsilon})}.$$
Letting $\eta$ tend to 0 we obtain $\|((\bar{u}_\alpha^\varepsilon - \bar{v})+\|_{L^\infty(Q_{\alpha,\varepsilon})} \leq \|((\bar{u}_\alpha^\varepsilon - \bar{v})+\|_{L^\infty(\partial_p Q_{\alpha,\varepsilon})}$. In order to prove the final result, we have to pass to the limit as $\varepsilon \to 0$ and then as $\alpha \to 0$.

Letting $\varepsilon$ tend to 0 is easy since $\bar{u}_\alpha$ is continuous (we may even argue in a slightly smaller domain/cylinder). Therefore

$$\|((\bar{u}_\alpha - m(\alpha)t - \bar{v})+\|_{L^\infty(Q_{\alpha,\varepsilon})} \leq \|((\bar{u}_\alpha - m(\alpha)t - \bar{v})+\|_{L^\infty(\partial_p Q_{\alpha,\varepsilon})}.$$  

Fix now $\alpha_0 > 0$ and $(y, s) \in Q_{\alpha_0}$. For all $0 < \alpha \leq \alpha_0$ we have

$$((\bar{u}_\alpha(y, s) - m(\alpha)t - \bar{v}(y, s))_+ \leq \|((\bar{u}_\alpha - m(\alpha)t - \bar{v})+\|_{L^\infty(\partial_p Q_{\alpha,\varepsilon})}.$$  

(6.5)

Let us observe that by the properties of the sup-convolution and the fact that $\bar{u}$ is upper-semi-continuous we have that $\limsup\bar{u}_\alpha \to \bar{u}$, passing to the limsup in (6.5) we deduce

$$(\bar{u}(y, s) - \bar{v}(y, s))_+ \leq \|((\bar{u} - \bar{v})+\|_{L^\infty(\partial_p \bar{Q})} \quad \forall (y, s) \in Q_{\alpha_0}.$$  

Since $\alpha_0$ is arbitrary we get $\|((\bar{u} - \bar{v})+\|_{L^\infty(Q)} \leq \|((\bar{u} - \bar{v})+\|_{L^\infty(\partial_p Q)}$ and the result is proved. □

Let us now prove the needed regularity properties on the tangential Hamiltonian $H_T$. We do it for a non-flat boundary for the sake of completeness.

**Lemma 6.5.** Assume (H$_Q$) and (H$_C$). The tangential Hamiltonian defined in (3.1) satisfies the following Lipschitz properties with respect $z \in \mathcal{H}$ and $p_H$

$$|H_T(z, t, p_H) - H_T(z, t, q_H)| \leq M_b|p_H - q_H|.$$  

(6.6)

Moreover, for any $z, z' \in \mathcal{H}$ and $t, t' \in [0, T]$

$$|H_T(z, t, p_H) - H_T(z', t', p_H)| \leq M|(z, t) - (z', t')||p_H| + m(|(z, t) - (z', t')|),$$  

where, if $M_b, M_1, L_b, m_1, \delta$ are given by (H$_C^1$) and (H$_C^2$),

$$M := (L_b + 2M_b(L_b + M_bL_n)\delta^{-1}),$$  

$L_n$ being the Lipschitz constant of $n_1$ and

$$m(t) = (L_b + 2M_1\delta^{-1})t + m_1(t) \quad \text{for } t \geq 0.$$  

**Proof.** The proof easily follows from Lemma 6.6 below and standard arguments. □

**Lemma 6.6.** Assume (H$_Q$) and (H$_C$). For any $(z, t), (z', t') \in \mathcal{H} \times [0, T]$ and for each control $a \in A_0(z, t)$, there exists a control $a' \in A_0(z', t')$ such that, if $C := L_b + M_bL_n$

$$|b_H(z, t, a) - b_H(z', t', a')| \leq (L_b + 2M_b\delta^{-1})|((z, t) - (z', t'))|$$  

$$|l_H(z, t, a) - l_H(z', t', a')| \leq 2M_1\delta^{-1}|((z, t) - (z', t'))| + m_1(|((z, t) - (z', t'))|).$$  

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Proof. Let us consider a control \( a \in A_0(z,t) \), i.e. \( b_H(z,t,a) \cdot n_1(z) = 0 \). Fix \((z', t') \in H \times [0, T]\), we have two possibilities. If \( b_H(z', t', a) \cdot n_1(z') = 0 \) the conclusion easily follows because \( a' = a \in A_0(z', t') \) and

\[
|b_H(z, t, a) - b_H(z', t', a)| \leq L_b |(z, t) - (z', t')|,
\]

(6.8)

\[
|l_H(z, t, a) - l_H(z', t', a)| \leq m_t |(z, t) - (z', t')|.
\]

(6.9)

Otherwise \( b_H(z', t', a) \cdot n_1(z') \neq 0 \). Let us suppose, for example, that \( b_H(z', t', a) \cdot n_1(z) > 0 \) (for the other sign the same argument will apply so we will not detail it). We first remark that by (Remark 6.7.) \( \mu \) the results of Lemma 6.5 and 6.6 still hold in the case of \( \mathcal{C} \).

\[
|b_H(z', t', a) \cdot n_1(z')| = |b_H(z', t', a) \cdot n_1(z') - b_H(z, t, a) \cdot n_1(z)| \leq \bar{C}' |(z, t) - (z', t')|
\]

(6.10)

with \( \bar{C}' := L_b + M_b L_n \). By the controllability assumption in (\( \mathcal{H}_C^1 \)) there exists a control \( a_1 \in A \) such that \( b_H(z', t', a_1) \cdot n_1(z') = -\delta n_1(z') \). We then set

\[
\bar{\mu} := \frac{\delta}{b_H(z', t', a) \cdot n_1(z') + \delta},
\]

since \( \bar{\mu} \in [0, 1] \), by the convexity assumption in (\( \mathcal{H}_C^1 \)), there exists a control \( a' \) such that

\[
\bar{\mu}(b_H(z', t', a), l_H(z', t', a)) + (1 - \bar{\mu})(b_H(z', t', a_1), l_H(z', t', a_1)) = (b_H(z', t', a'), l_H(z', t', a')).
\]

By construction \( b_H(z', t', a') \cdot n_1(z') = 0 \), therefore \( a' \in A_0(z', t') \). Moreover, since

\[
(1 - \bar{\mu}) = \frac{b_H(z', t', a) \cdot n_1(z')}{b_H(z', t', a) \cdot n_1(z') + \delta}
\]

by (6.10), we have

\[
|b_H(z', t', a) - b_H(z', t', a')| \leq (1 - \bar{\mu}) |b_H(z', t', a) - b_H(z', t', a_1)| \leq 2M_b \bar{C}' \delta^{-1} |(z, t) - (z', t')|,
\]

and the same inequality holds for \( l_H \), replacing \( M_b \) by \( M_l \). Hence, thanks to (6.8)-(6.9), we obtain

\[
|b_H(z, t, a) - b_H(z', t', a')| \leq (L_b + 2M_b \bar{C}' \delta^{-1}) |(z, t) - (z', t')|
\]

and

\[
|l_H(z, t, a) - l_H(z', t', a')| \leq 2M_l \bar{C}' \delta^{-1} |(z, t) - (z', t')| + m_t |(z, t) - (z', t')|.
\]

and this concludes the proof.

\[ \square \]

Remark 6.7. The results of Lemma 6.5 and 6.6 still hold in the case of \( \mathcal{H}_C^{reg} \), changing the constants in (6.6) and (6.7) and in the result of Lemma 6.6. The simplest way to prove it is the following: we only do it for \( b_1, b_2 \) but a correct argument would require a proof in \( (b_1, l_1), (b_2, l_2) \).

We first remark that if

\[
b_H(z, t, a) = \mu b_1(z, t, \alpha_1) + (1 - \mu)b_2(z, t, \alpha_2),
\]

and if \(|(z, t) - (z', t')|\) is small enough, we may assume without loss of generality that, for \( i = 1, 2, \)

\[
b_i(z, t, \alpha_i) \cdot n_i(z) \geq 3(L_b + 2M_b \bar{C}' \delta^{-1}) |(z, t) - (z', t')|.
\]

(6.11)
Indeed, by the controllability assumption in (H4C), there exists a control \( \alpha_i \in A_i \) such that \( b_i(z,t,\hat{\alpha}_i) \cdot n_i(z) = \delta n_i(z) \). Then, by taking \( |(z,t) - (z',t')| \) small enough, we can always assume that \( 3(L_b + 2M_bC\delta^{-1})|(z,t) - (z',t')| \) is between \( b_i(z,t,\hat{\alpha}_i) \cdot n_i(z) \) and \( b_i(z,t,\alpha_i) \cdot n_i(z) \). We can then choose \( \mu_i \in [0,1] \) such that
\[
(\mu_i b_i(z,t,\alpha_i) + (1-\mu_i)b_i(z,t,\hat{\alpha}_i)) \cdot n_i(z) = 3(L_b + 2M_b\tilde{C}\delta^{-1})|(z,t) - (z',t')|.
\]
Finally Assumption (H3C) ensures that there exists controls \( \tilde{\alpha}_i \) such that
\[
b_i(z,t,\tilde{\alpha}_i) = \mu_i b_i(z,t,\alpha_i) + (1-\mu_i)b_i(z,t,\hat{\alpha}_i).
\]
To obtain a new \( b_H(z,t,\tilde{a}) \), we choose \( \tilde{\mu} \in [0,1] \) such that
\[
[\tilde{\mu} b_1(z,t,\tilde{\alpha}_1) + (1-\tilde{\mu})b_2(z,t,\tilde{\alpha}_2)] \cdot n_1(z) = 0.
\]
To conclude we remark that a careful examination of the estimate on \( \tilde{\mu} \) in the proof of Lemma 6.6 shows that, if we start from a control \( \tilde{a} \in A_0^{reg}(z,t) \) verifying (6.11) the associated control \( \tilde{a}' \in A_0(z',t') \) is in fact in \( A_0^{reg}(z',t') \).

**Remark 6.8.** If the \( b_i \) are only assumed to be continuous, we have similar estimates involving the modulus of continuity \( m_{b_i} \) instead of the Lipschitz constant \( L_b \) (as we did for the \( l_i \) with \( m_{l_i} \)).

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