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On the Ball-Marsden-Slemrod obstruction for bilinear control systems

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Abstract—In this paper we present an extension to the case of $L^1$-controls of a famous result by Ball–Marsden–Slemrod on the obstruction to the controllability of bilinear control systems in infinite dimensional spaces.

I. INTRODUCTION

A. Bilinear control systems

Let $X$ be a Banach space, $A : D(A) \to X$ a linear operator in $X$ with domain $D(A)$, $B : X \to X$ a linear bounded operator and $\psi_0$ an element in $X$.

We consider a following bilinear control system on $X$

\[
\begin{cases}
\dot{\psi}(t) = A\psi(t) + u(t)B\psi(t), \\
\psi(0) = \psi_0,
\end{cases}
\]

where $u : [0, +\infty) \to \mathbb{R}$ is a scalar function representing the control.

Assumption 1: The pair $(A, B)$ of linear operators in $X$ satisfies

1) the operator $A$ generates a $C^0$-semigroup of linear bounded operators on $X$.
2) the operator $B$ is bounded.

Definition 1: Let $(A, B)$ satisfy Assumption 1 and let $T > 0$. A function $\psi : [0, T] \to X$ is a mild solution of (1) if for every $t$ in $[0, T]$,

\[\psi(t) = e^{tA}\psi_0 + \int_0^t e^{(t-s)A}B\psi(s)u(s)ds.\]

Equation (2) is often called Duhamel formula. Existence and uniqueness of mild solutions for equation (1) is given by the following result (see, for instance, Proposition 2.1 and Remark 2.7 in [BMS82]).

Proposition 1: Assume that $(A, B)$ satisfies Assumption 1. Then, for every $\psi_0$ in $X$, for every $u$ in $L^1_{\text{loc}}([0, +\infty), \mathbb{R})$, there exists a unique mild solution $t \mapsto \Upsilon_{t, 0}^{u}\psi_0$ to the Cauchy problem (1). Moreover, for every $\psi_0$ in $X$, the end-point mapping $\Upsilon_{s, 0}\psi_0 : [0, +\infty) \times L^1_{\text{loc}}([0, +\infty), \mathbb{R}) \to X$ is continuous.

Definition 2: Assume that $(A, B)$ satisfies Assumption 1 and let $\mathcal{U}$ be a subset of $L^1_{\text{loc}}([0, +\infty), \mathbb{R})$. For every $\psi_0$ in $X$, the attainable set from $\psi_0$ with controls in $\mathcal{U}$ is defined as

\[\mathcal{A}(\psi_0, \mathcal{U}) = \bigcup_{T \geq 0} \bigcup_{u \in \mathcal{U}} \{\Upsilon_{T, 0}^u\psi_0\}.\]

Our main result is the following property of the attainable set of system (1) with $L^1$ controls.

Theorem 2: Assume that $(A, B)$ satisfies Assumption 1. Then, for every $\psi_0$ in $X$, the attainable set $\mathcal{A}(\psi_0, L^1_{\text{loc}}([0, +\infty), \mathbb{R}))$ from $\psi_0$ with $L^1_{\text{loc}}$ controls is contained in a countable union of compacts subsets of $X$.

The Ball–Marsden–Slemrod obstruction

Our main result, Theorem 2 is an extension of the well-known Ball–Marsden–Slemrod obstruction to controllability (see also [ILT06]) which is as follows.

Theorem 3 (Theorem 3.6 in [BMS82]): Assume that $(A, B)$ satisfies Assumption 1. Then, for every $\psi_0$ in $X$, the attainable set $\mathcal{A}(\psi_0, L^r_{\text{loc}}([0, +\infty), \mathbb{R}))$ from $\psi_0$ with $L^r_{\text{loc}}$ controls, $r > 1$, is contained in a countable union of compacts subsets of $X$.

A consequence of Theorem 3 to the framework of the conservative bilinear Schrödinger equation is given by Turinici.

Theorem 4 (Theorem 1 in [Tur00]): Assume that $(A, B)$ satisfies Assumption 1. Then, for every $\psi_0$ in $X$, the set $\cup_{t \geq 0} A\psi_0, \cup_{t \geq 1} L^1_{\text{loc}}([0, +\infty), \mathbb{R}))$ is contained in a countable union of compacts subsets of $X$.

Theorems 2 and 3 are basically empty in the case in which $X$ is finite dimensional, since, in this case, $X$ itself is a countable union of compact sets. On the other hand, when $X$ is infinite dimensional, these results represent a strong topological obstruction to the exact controllability. Indeed, compact subsets of an infinite dimensional Banach space have empty interiors and so is a countable union of closed subsets with empty interiors (as a consequence of Baire Theorem).

Whether the non-controllability result of Ball, Marsden, and Slemrod, Theorem 3 holds for $L^1$ control has been an open question for decades. Indeed, the proof of Theorem 3 does not apply directly to the $L^1$ case. To see what fails let...
us briefly recall the method used in [BMS82] for the proof of Theorem 3. The first step is to write

\[ A(\psi_c, L_{t,0}^{r)}((0, +\infty), \mathbb{R})) \]

\[ = \bigcup_{t \geq 0} \bigcup_{r > 1} \bigcup_{u \in L^r((0, t), \mathbb{R})} \{ \psi_c(u, t) \} \]

\[ = \bigcup_{l \in \mathbb{N}} \bigcup_{n \in \mathbb{N}} \bigcup_{k \in \mathbb{N}} \bigcup_{0 \leq t \leq l} \bigcup_{\|u\|_{L^1 + \infty} \leq k} \{ \psi_c(u, t) \} \]

Hence it is sufficient to prove that, for every \((l, m, k) \in \mathbb{N}^3\), the set

\[ A^{l, m, k} = \bigcup_{0 \leq t \leq l} \bigcup_{\|u\|_{L^1 + \infty} \leq k} \{ \psi_c(u, t) \} \]

has compact closure in \(X\). To this end, one considers a sequence \( (\psi_n)_{n \in \mathbb{N}} \) in \( A^{l, m, k} \), associated with a sequence of times \( (t_n)_{n \in \mathbb{N}} \) in \([0, l]\) and a sequence of controls \( (u_n)_{n \in \mathbb{N}} \) in the ball of radius \( k \) of \( L^{1 + 1/m}(0, +\infty, \mathbb{R}) \). By compactness of \([0, l]\), up to extraction, one can assume that \( (t_n)_{n \in \mathbb{N}} \) tends to \( t_\infty \) in \([0, l]\). By Banach–Alaoglu–Bourbaki Theorem, the balls of \( L^{1 + 1/m}(0, +\infty, \mathbb{R}) \) are weakly (sequentially) compact and, hence, up to extraction, one can assume that \( (u_n)_{n \in \mathbb{N}} \) converges weakly in \( L^{1 + 1/m}(0, +\infty, \mathbb{R}) \) to some \( u_\infty \). The hard step of the proof (Lemma 3.7 in [BMS82]) is then to show that \( \psi_c(u_\infty, t) \) tends to \( \psi_c(u_\infty, t) \) as \( n \) tends to infinity.

A crucial point in the proof of Theorem 3 given in [BMS82] is the fact that the closed balls of \( L^p, p > 1 \) are weakly sequentially compact. This is no longer true for the balls of \( L^1 \), and this prevents a direct extension of the proof of Theorem 3 to Theorem 2. Here we present a brief and self-contained proof of Theorem 2 mainly based on Dyson expansions and basic compactness properties on Banach spaces.

An alternative proof of Theorem 3, not relying on the reflectiveness of the set of admissible controls, has been recently given in [BCC17]. The proof applies to a very large class of controls (namely, Radon measures) which contains locally integrable functions, and for its generality it is technically quite involved, in contrast with the simplicity of the underlying ideas. It applies also, with minor modifications, to nonlinear problems [CT18].

II. BASIC FACTS ABOUT TOPOLOGY IN BANACH SPACES

A. Notations

The Banach space \( X \) is endowed with norm \( \| \cdot \| \). For every \( \psi_c, \psi, \| \psi - \psi_c \| < r \), we have

\[ B_X(\psi_c, r) = \{ \psi \in X | \| \psi - \psi_c \| < r \} \]

In the following, all we need to know about generators of \( C^0 \)-semigroup is the classical result stated in Proposition 5 (see Chapter VII of [HP57]).

Proposition 5: Assume that \( A \) generates a \( C^0 \)-semigroup. Then there exist \( M, \omega > 0 \) such that \( \|e^{At}\| \leq Me^{\omega t} \) for every \( t \geq 0 \).

B. Compact subset of Banach spaces

Definition 3: Let \( X \) and \( Y \) be a Banach space and \( Z \) be a subset of \( X \). A family \( (O_i)_{i \in I} \) is an open cover of \( Y \) if \( O_i \) is open in \( X \) for every \( i \in I \) and \( Y \subseteq \bigcup_{i \in I} O_i \).

Definition 4: Let \( X \) be a Banach space. A subset \( Y \) of \( X \) is said to be compact if from any open cover of \( Y \), it is possible to extract a finite cover of \( Y \).

Definition 5: Let \( X \) be a Banach space. A subset \( Y \) of \( X \) is said to be sequentially compact if from any sequence \( (\psi_n)_{n \in \mathbb{N}} \) converging in \( Y \) and taking value in \( Y \), it is possible to extract a subsequence \( (\psi_{n_i})_{n_i \in \mathbb{N}} \) converging in \( Y \).

Definition 6: Let \( X \) be a Banach space. A subset \( Y \) of \( X \) is said to be totally bounded if for every \( \varepsilon > 0 \), there exist \( N \in \mathbb{N} \) and a finite family \( \{x_i\}_{1 \leq i \leq N} \) in \( X \) such that

\[ Y \subseteq \bigcup_{i=1}^N B_X(x_i, \varepsilon) \]

Proposition 6: Let \( X \) be a Banach space. For every subset \( Y \) of \( X \), the following assertions are equivalent:

1) \( Y \) is compact.
2) \( Y \) is sequentially compact.
3) \( Y \) is completely bounded.
4) \( Y \) is closed and totally bounded.

Proposition 7: Let \( X \) be a Banach space, \( N \) in \( \mathbb{N} \) and \( \{Y_i\}_{1 \leq i \leq N} \) a finite family of compact subsets of \( X \). Then, the finite sum

\[ \sum_{i=1}^N Y_i = \{ y_1 + y_2 + \ldots + y_N \mid y_i \in Y_i, i = 1, \ldots, N \} \]

is compact as well.

Proposition 8: Let \( X \) be a Banach space, \( N \) in \( \mathbb{N} \) and \( \{Y_i\}_{1 \leq i \leq N} \) a finite family of totally bounded subsets of \( X \). Then, the finite sum

\[ \sum_{i=1}^N Y_i = \{ y_1 + y_2 + \ldots + y_N \mid y_i \in Y_i, i = 1, \ldots, N \} \]

is totally bounded as well.

Proposition 9: Let \( X \) be a Banach space, \( T > 0 \) and \( (A, B) \) satisfies Assumption 1. Define the mapping

\[ F : [0, T] \times [0, T] \times X \rightarrow X \]

\[ (s, t, \psi) \mapsto e^{(t-s)A}B\psi \]
Then, for every totally bounded subset $Y$ of $X$, the set $F([0,T] \times [0,T] \times Y)$ is totally bounded as well.

Proof: We claim that $G : (t, \psi) \mapsto e^{tA}\psi$ is jointly continuous in its two variables. Indeed, for every $\psi, \psi_0$ in $X$, for every $t, t_0 \geq 0$,

$$\|e^{tA}\psi - e^{t_0A}\psi_0\| \leq \|e^{tA}(\psi - \psi_0)\| + \|e^{(t_0-t)A}\psi_0\| \leq Me^{t_0}\|\psi - \psi_0\| + \|e^{(t_0-t)A}\psi_0\|.$$  

This last quantity tends to zero as $(t, \psi)$ tends to $(t_0, \psi_0)$. As a consequence, $F$ is continuous (as composition of continuous functions).

If $Y$ is totally bounded, the topological closure $\bar{Y}$ of $Y$ is compact (because the ambient space $X$ is complete). Hence $[0,T] \times [0,T] \times \bar{Y}$ is compact. By continuity, $F([0,T] \times [0,T] \times \bar{Y})$ is compact, hence is totally bounded. The set $F([0,T] \times [0,T] \times Y)$, which is contained in $F([0,T] \times [0,T] \times \bar{Y})$, is therefore, totally bounded as well.  

C. Partition of unity in Banach spaces

Definition 7: Let $X$ be a Banach space. A family $(x_i)_{i \in I}$ of points of $X$ is locally finite if for every $x$ in $X$ and every $r > 0$, the cardinality of the set

$$\left( \bigcup_{i \in I} \{x_i\} \right) \cap B_X(x, r)$$  

is finite.

Definition 8: Let $X$ be a Banach space, $Y$ a subset of $X$, and $(O_i)_{i \in I}$ be an open cover of $Y$. A family $(\phi_i)_{i \in I}$ of continuous functions from $Y$ to $[0,1]$ is called a partition of the unity of $Y$ adapted to the cover $(O_i)_{i \in I}$ if

(i) for every $i \in I$, $\phi_i(x) = 0$ for every $x \notin O_i$;

(ii) $\sum_{i \in I} \phi_i(x) = 1$ for every $x$ in $Y$.

Proposition 10: Let $X$ be a Banach space, $Y$ a subset of $X$, $\delta > 0$, $(x_j)_{j \in J}$ a locally finite family of points in $Y$ such that $Y \subset \bigcup_{j \in J} B_X(x_j, \delta)$. Then, there exists $(\phi_j)_{j \in J}$ a partition of the unity adapted to the open cover $(B(x_j, 2\delta))_{j \in J}$ of $Y$.

Moreover, if a family $(\phi_j)_{j \in J}$ is a partition of the unity adapted to the open cover $(B_X(x_j, 2\delta))_{j \in J}$, then for every $x$ in $Y$, $\|x - \sum_{j \in J} \phi_j(x) x_j\| \leq 2\delta$.

Proof: We first prove the existence of a partition of the unity adapted to the open cover $(B_X(x_j, 2\delta))_{j \in J}$ of $Y$. To this end, we define, for every $j$ in $J$, the continuous functions $\varphi_j : X \to [0,1]$ by

$$\begin{align*}
\varphi_j(x) &= 1, & \text{if } \|x - x_j\| < \delta, \\
\varphi_j(x) &= 2 - \|x - x_j\|/\delta, & \text{if } \delta \leq \|x - x_j\| < 2\delta, \\
\varphi_j(x) &= 0, & \text{if } 2\delta \leq \|x - x_j\|. 
\end{align*}$$

Since the family $(x_j)_{j \in J}$ is locally finite, the sum $\sum_{j \in J} \varphi_j(x)$ converges for every $x$ in $Y$. Moreover, since $Y \subset \bigcup_{j \in J} B(x_j, \delta)$, the function $x \mapsto \sum_{j \in J} \varphi_j(x)$ does not vanish on $Y$. For every $j_0$ in $J$, we define $\phi_{j_0}$ by

$$\phi_{j_0}(x) = \varphi_{j_0}(x) \frac{1}{\sum_{j \in J} \varphi_j(x)},$$

and the family $(\phi_j)_{j \in J}$ is a partition of the unity adapted to the open cover $(B_X(x_j, 2\delta))_{j \in J}$ of $Y$.

We now prove the second point of Proposition 10. Let $(\phi_j)_{j \in J}$ be a partition of unity of $Y$ adapted to the cover $(B_X(x_j, 2\delta))_{j \in J}$. Then, for every $x$ in $Y$,

$$\|x - \sum_{j \in J} \phi_j(x) x_j\| = \sum_{j \in J} \phi_j(x)\|x - x_j\| \leq \sum_{j \in J} \phi_j(x)\|x - x_j\| = 2\delta \sum_{j \in J} \phi_j(x) \leq 2\delta,$$

which concludes the proof.

III. DYSON EXPANSION

A. The Dyson Operators

For every $u$ in $L_{loc}^1([0,\infty), \mathbb{R})$, $p \in \mathbb{N}$, and $t \geq 0$ we define the linear bounded operator $W_p(t,u) : X \to X$ recursively by

$$W_0(t,u)\psi = e^{(t-s)A}\psi, \quad W_p(t,u)\psi = \int_0^t e^{(t-s)A}Bw_{p-1}(s,u)\psi u(s)ds,$$

for $p \geq 1$, for every $\psi$ in $X$. We have the following estimate on the norm of the operator.

Proposition 11: For every $u$ in $L_{loc}^1([0,\infty), \mathbb{R})$, $p \in \mathbb{N}$, and $t \geq 0$

$$\|W_p(t,u)\| \leq \frac{Me^{c^+t}\|B\|p!\|\int_0^t |u(s)|ds\|^p}{p!}.$$

Proof: We prove the result by induction on $p$ in $\mathbb{N}$. For $p = 0$ the result clearly follows from Proposition 5. Assume that the result holds for $p \geq 0$. Then, for every $\psi$ in $X$,

$$\|W_{p+1}(t,u)\| \leq \int_0^t e^{(t-s)A}Bw_{p}(s,u)\psi u(s)ds,$$

$$\leq M \int_0^t e^{(t-s)A}\|B\|\frac{e^{c^+t}\|B\|p!\|\int_0^t |u(\tau)|d\tau\|^p}{p!}u(s)ds,$$

$$\leq Me^{c^+t}\|B\|p!\left(\int_0^t |u(\tau)|d\tau\right)^{p+1}/(p+1)!.$$

The last inequality follows from Proposition 5. We conclude the proof by induction on $p$.  

■
B. A compactness property

Lemma 12: For every \( j \) in \( \mathbb{N} \), \( T \geq 0 \) and \( K \geq 0 \), and \( \psi \) in \( X \) the set

\[
W_{ij} = \{ W_j(t, u) \psi \mid 0 \leq t \leq T, \| u \|_{L} \leq K \}, \quad (3)
\]

is totally bounded.

Proof: We prove the result by induction on \( j \) in \( \mathbb{N} \).

For \( j = 0 \), consider \( W_0^{T,K} = \{ e^{tA} \psi, 0 \leq t \leq T \} \) and let \((u_n)_{n \in \mathbb{N}} \) be a sequence in \( W_0^{T,K} \). Then there exists a sequence \((u_n)_{n \in \mathbb{N}} \) such that \( w_n = e^{t_nA} \psi \) for every \( n \).

By Proposition 10, and moreover, for every \( x \) in \( X \), we get, for every \( t \),

\[
\int_0^t e^{(t-s)A}B \, \psi \, W_j(s, u) \, \psi \, ds \leq M e^{\omega t} \| \psi \| B \| \int_0^t |u(s)| ds \|
\]

and the conclusion follows by Gronwall lemma (see [BMS82, Lemma 2.6]).

From (5) and (6), one deduces that

\[
W_{ij+1} \subset \bigcup_{i=1}^{N_j} B_X (y_i, (2K + 1)\delta) = B_X (y_i, \varepsilon).
\]

This proves that \( W_{ij+1} \) is totally bounded and concludes the proof.

C. Convergence of the Dyson expansion

Proposition 13: For every \( u \) in \( L^1([0, +\infty), \mathbb{R}) \), \( t \geq 0 \), and \( \psi \in X \),

\[
\| \Upsilon_{t,0}^u \psi \| \leq M e^{\omega t} \| \psi \| \exp \left( M e^{\omega t} \| B \| \int_0^t |u(s)| ds \right)
\]

Proof: By Duhamel formula (2) and Proposition 5,

\[
\| \Upsilon_{t,0}^u \psi \| \leq e^{tA} \psi + \int_0^t e^{(t-s)A}B \Upsilon_{s,0}^u \psi \, u(s) \, ds \|
\]

and the conclusion follows by Gronwall lemma (see [BMS82, Lemma 2.6]).

Proposition 14: For every \( u \) in \( L^1([0, +\infty), \mathbb{R}) \), \( p \) in \( \mathbb{N} \), \( t \geq 0 \), and \( \psi \in X \),

\[
\lim_{p \to \infty} \left\| \int_0^t e^{(t-s)A} B W_p(s, t) \Upsilon_{s,0}^u \psi \, u(s) \, ds \right\| = 0.
\]

Proof: Consider

\[
\left\| \int_0^t e^{(t-s)A} B W_p(s, t) \Upsilon_{s,0}^u \psi \, u(s) \, ds \right\| \leq \int_0^t \| e^{(t-s)A} \| \| B \| \| W_p(s, t) \| \| \Upsilon_{s,0}^u \psi \| \| u(s) \| ds
\]

and recall that \( \| W_p(s, t) \| \) tends to zero as \( p \) tends to infinity (Proposition 11).

Proposition 15: For every \( u \) in \( L^1_{loc}([0, +\infty), \mathbb{R}) \), \( p \) in \( \mathbb{N} \), \( t \geq 0 \), and \( \psi \) in \( X \),

\[
\Upsilon_{t,0}^u \psi = \sum_{p=0}^{\infty} W_p(t, 0) \psi.
\]
Proof: Applying iteratively $p$-times Duhamel formula (2), one gets
\[
\Upsilon^u_{t,0} \psi_0 = e^{tA} \psi_0 + \int_0^t e^{(t-s_1)A} Bu(s_1) \Upsilon^u_{s_1,0} \psi_0 ds_1 \\
= e^{tA} \psi_0 + \int_0^t e^{(t-s_1)A} Bu(s_1) e^{s_1A} \psi_0 ds_1 \\
+ \int_0^t e^{(t-s)A} BW_1(s,t) \Upsilon^u_{s,0} \psi_0 u(s)u(s)ds \\
= \sum_{j=1}^p W_p(t,0) \psi_0 \\
+ \int_0^t e^{(t-s)A} BW_p(s,t) \Upsilon^u_{s,0} \psi_0 u(s)ds.
\]
Hence, for every $p \geq 1$,
\[
\Upsilon^u_{t,0} \psi_0 - \sum_{j=0}^p W_j(t,0) \psi_0 \\
= \int_0^t e^{(t-s)A} BW_p(s,t) \Upsilon^u_{s,0} \psi_0 u(s)ds.
\]
and the result follows from Proposition 14 as $p$ tends to $\infty$.

IV. PROOF OF THEOREM 2

We proceed now to the proof of Theorem 2. First of all, notice that, for every $\psi_0$ in $X$,
\[
A(\psi_0, L^1_{loc}([0, +\infty), R)) \\
= \bigcup_{l \in N} \bigcup_{m \in N} \{ \Upsilon^u_{t,0} \psi_0, \|u\|_{L^1} \leq l, 0 \leq t \leq m \},
\]
and it is enough to prove that, for every $l$ and $m$ in $N$, the set
\[
\{ \Upsilon^u_{t,0} \psi_0, \|u\|_{L^1} \leq l, 0 \leq t \leq m \}
\]
is totally bounded.

Let $\varepsilon > 0$. From the convergence of the Dyson expansion (Proposition 15) and the bound on the operators $W_j$ (Proposition 11), there exists an integer $N_\varepsilon$ such that
\[
\left\| \sum_{j=0}^{N_\varepsilon} W_j(t, u) \psi_0 \right\| \leq \frac{\varepsilon}{2} \tag{7}
\]
for every $t$ in $[0, m]$ and every $u$ such that $\|u\|_{L^1} \leq l$. For each $j = 1, \ldots, N_\varepsilon$, the sets $W_j^{m,l}$, defined by (3), are totally bounded (Lemma 12), hence their sum
\[
\sum_{j=0}^{N_\varepsilon} W_j^{m,l}
\]
is totally bounded as well (Proposition 8). Hence there exists a family $(x_i)_{1 \leq i \leq N_1}$ of points of $\sum_{j=0}^{N_\varepsilon} W_j^{m,l}$ such that
\[
\sum_{j=0}^{N_\varepsilon} W_j^{m,l} \subset \bigcup_{i=1}^{N_1} B_X (x_i, \frac{\varepsilon}{2}). \tag{8}
\]
Gathering (7) and (8), one gets
\[
\sum_{j=0}^{\infty} W_j^{m,l} \subset \bigcup_{i=1}^{N_1} B_X (x_i, \varepsilon),
\]
which concludes the proof of Theorem 2.

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