ON THE CONTROLLABILITY OF PARABOLIC SYSTEMS WITH A
NONLINEAR TERM INVOLVING THE STATE AND THE
GRADIENT

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Abstract. We present some results concerning the controllability of a quasi-linear parabolic equation
(with linear principal part) in a bounded domain of \( \mathbb{R}^N \) with Dirichlet boundary conditions. We analyze
the controllability problem with distributed controls (supported on a small open subset) and boundary
controls (supported on a small part of the boundary). We prove that the system is null and approximate
controllable at any time if the nonlinear term \( f(y, \nabla y) \) grows slower than \( |y| \log^{3/2}(1 + |y| + |\nabla y|) \) at
infinity (in general, in this case, in the absence of control, blow-up occurs). The proofs use global Carleman
estimates, parabolic regularity and the fixed point method.

Key words. controllability, parabolic equations, nonlinear gradient terms

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1. Introduction and main results. Let \( \Omega \subset \mathbb{R}^N \) be a bounded domain with boundary \( \partial \Omega \) of class \( C^{2} \). Let \( \mathcal{O} \subset \Omega \) be a nonempty open subset, let \( \gamma \subset \partial \Omega \) be a
nonempty relative open subset of the boundary and assume that \( T > 0 \). We will use the following notation: \( Q = \Omega \times (0, T) \), \( \Sigma = \partial \Omega \times (0, T) \). For any \( p \in [1, +\infty] \), we will
denote by \( \| \cdot \|_p \) the usual norm in \( L^p(Q) \).

We will consider parabolic systems of the form

\[
\begin{align*}
\begin{cases}
\partial_t y - \Delta y + f(y, \nabla y) &= v1_{\mathcal{O}} & \text{in } Q, \\
y(0, x) &= 0 & \text{on } \Sigma, \\
y(x, 0) &= g_0(x) & \text{in } \Omega,
\end{cases}
\end{align*}
\]

and

\[
\begin{align*}
\begin{cases}
\partial_t y - \Delta y + f(y, \nabla y) &= 0 & \text{in } Q, \\
y(0, x) &= v1_{\gamma} & \text{on } \Sigma, \\
y(x, 0) &= g_0(x) & \text{in } \Omega,
\end{cases}
\end{align*}
\]

where \( g_0 \) and \( v \) are given in appropriate spaces. In (1) and (2),

\[ f : \mathbb{R} \times \mathbb{R}^N \to \mathbb{R} \]

is a locally Lipschitz-continuous function and \( 1_{\mathcal{O}} \) and \( 1_{\gamma} \) denote the characteristic
functions of the sets \( \mathcal{O} \) and \( \gamma \), respectively. We will assume that \( g_0 \in W^{1,\infty}(\Omega) \cap H^1_0(\Sigma) \)
(for simplicity), \( v \in L^\infty(\mathcal{O} \times (0, T)) \) in (1) and \( v \in L^\infty(\gamma \times (0, T)) \) in (2).

The main goal of this paper is to analyze the controllability properties of (1) and (2). It will be said that (1) (resp. (2)) is null controllable at time \( T \) if, for each \( g_0 \in W^{1,\infty}(\Omega) \cap H^1_0(\Omega) \), there exists \( v \in L^\infty(\mathcal{O} \times (0, T)) \) (resp. \( v \in L^\infty(\gamma \times (0, T)) \)) such that the corresponding initial boundary problem (1) (resp. (2)) admits a solution

\[ y \in C^0([0, T]; L^2(\Omega)) \]

satisfying

\[ y(x, T) = 0 \quad \text{in } \Omega. \]

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On the other hand, it will be said that (1) (resp. (2)) is approximately controllable in $L^2(\Omega)$ at time $T$ if, for any $y_0 \in W^{1,\infty}(\Omega) \cap H_0^1(\Omega)$, any $y_d \in L^2(\Omega)$ and any $\varepsilon > 0$, there exists a control $v \in L^{\infty}(\mathbb{R} \times (0,T))$ (resp. a control $v \in L^{\infty}(\gamma \times (0,T))$) such that the corresponding initial boundary problem (1) (resp. (2)) possesses a solution $y \in C^0([0,T];L^2(\Omega))$, with

$$\|y(\cdot, T) - y_d\|_2 \leq \varepsilon.$$ 

The controllability of linear and semilinear parabolic systems has been analyzed in several recent papers. Among them, let us mention [3], [F1], [F], [H], [AB] and [FZ2] in what concerns null controllability and [FPZ], [Z2] and [FZ2] for approximate controllability.

This paper generalizes all previous results, in particular, those in [FZ2], where the nonlinear term is assumed to be of the form $f(y)$.

Notice that, under the hypothesis above, we can write

$$f(s, p) = f(0, 0) + g(s, p) s + G(s, p) \cdot p \quad \forall (s, p) \in \mathbb{R} \times \mathbb{R}^N$$

for some $L^\infty_{\text{loc}}$ functions $g$ and $G$. These are respectively given by

$$g(s, p) = \int_0^1 \frac{\partial f}{\partial s}(\lambda s, \lambda p) \, d\lambda, \quad G_i(s, p) = \int_0^1 \frac{\partial f}{\partial \lambda_i}(\lambda s, \lambda p) \, d\lambda \quad \text{for } 1 \leq i \leq N.$$

Our first result is the following one:

**Theorem 1.1.** Assume that $f$ is locally Lipschitz-continuous, $f(0,0) = 0$ and

$$\lim_{|s| \to \infty} \frac{|g(s, p)|}{\log^{3/2}(1 + |s|)} = 0, \quad \lim_{|s| \to \infty} \frac{|G(s, p)|}{\log^{1/2}(1 + |s| + |p|)} = 0.$$

Then (1) is null controllable at any time $T > 0$.

**Remark 1.1.** This result generalizes at least two cases that have been studied exhaustively before. First, the case of a globally Lipschitz-continuous function $f$, i.e. when $g \in L^{\infty}(\mathbb{R} \times \mathbb{R}^N)$ and $G \in L^{\infty}(\mathbb{R} \times \mathbb{R}^N)^N$. In this case, $f$ is a function with sublinear behaviour at infinity and the proof of the corresponding controllability result is easier (cf. [IY]). Secondly, the case where $G \equiv 0$ and $g = g(s)$ and satisfies

$$\lim_{|s| \to \infty} \frac{|g(s)|}{\log^{3/2}(1 + |s|)} = 0.$$

The proof is again easier (cf. [FZ2]).

**Remark 1.2.** In [FZ2], it is proved that, for each $\beta > 2$, there exist functions $f = f(s)$ with $f(0) = 0$ and

$$|f(s)| \sim |s|^{\beta} (1 + |s|) \quad \text{as } |s| \to \infty,$$

such that (1) is not null-controllable for all $T > 0$. In view of Theorem 1.1, we see that, when $f$ satisfies (8) with $3/2 \leq \beta \leq 2$, the null-controllability problem of (1) is an open question.

**Remark 1.3.** Theorem 1.1 says in particular that, under assumption (6), for each $y_0$ there exists a control $v$ such that (1) possesses a solution globally defined in $[0, T]$. This claim is not true for any right hand side and any $y_0 \in W^{1,\infty}(\Omega) \cap H_0^1(\Omega)$, since we are in the range in which blow-up may occur.
A consequence of Theorem 1.1 is the approximate controllability of (1). In this case, we will assume that \( f \) verifies (5) and (9), a condition slightly different from (6) (with \( f(0,0) \) not necessary equal to 0). We will also assume that, for some \( y_0^* \in W^{1,\infty}(\Omega) \cap H^1_0(\Omega) \) and \( v^* \in L^\infty(\mathcal{O} \times (0,T)) \), system (1) admits a global solution \( y^* \in C^0([0,T]; W^{1,\infty}(\Omega)) \). Of course, this holds immediately when

\[
f(0,0) = 0,
\]
a case in which \( y^* \equiv 0 \) solves (1) with \( y_0^* \equiv 0 \) and \( v^* \equiv 0 \). Thus, our second main result is the following one:

**Theorem 1.2.** Let \( T > 0 \). Assume that \( f : \mathbb{R} \times \mathbb{R}^N \to \mathbb{R} \) is locally Lipschitz-continuous and verifies

\[
\lim_{|s,p| \to \infty} \frac{1}{\log^{3/2}(1 + |s| + |p|)} \left| \int_0^1 \frac{\partial f}{\partial s}(s_0 + \lambda s, p_0 + \lambda p) d\lambda \right| = 0,
\]

\[
(9)
\]

uniformly in \((s_0, p_0) \in K\), for every compact set \( K \subset \mathbb{R} \times \mathbb{R}^N \). Also, assume that (1) admits at least one global solution \( y^* \in C^0([0,T]; W^{1,\infty}(\Omega)) \), corresponding to \( y_0^* \in W^{1,\infty}(\Omega) \cap H^1_0(\Omega) \) and \( v^* \in L^\infty(\mathcal{O} \times (0,T)) \). Then (1) is approximately controllable at any time \( T \).

**Remark 1.4.** In fact, it will be seen in §4 that, for systems like (1), the approximate controllability result is a consequence of the exact controllability to the trajectories in \( C^0([0,T]; W^{1,\infty}(\Omega)) \).

**Remark 1.5.** Again, Theorem 1.2 generalizes two known results. First, the case where \( f \) is globally Lipschitz-continuous, i.e. the case in which \( \partial f/\partial s \) and \( \partial f/\partial p_i \) \((1 \leq i \leq N)\) are uniformly bounded (cf. [Z2]). On the other hand, the case in which \( G \equiv 0, g = g(s) \) and (7) is satisfied (cf. [FZ2]).

**Remark 1.6.** In particular, (9) holds whenever \( \partial f/\partial s \) and \( \partial f/\partial p_i \) \((1 \leq i \leq N)\) satisfy

\[
\lim_{|s,p| \to \infty} \frac{\left| \frac{\partial f}{\partial s}(s, p) \right|}{\log^{3/2}(1 + |s| + |p|)} = 0, \quad \lim_{|s,p| \to \infty} \frac{\left| \frac{\partial f}{\partial p_i}(s, p) \right|}{\log^{1/2}(1 + |s| + |p|)} = 0.
\]

On the other hand, the assumptions (9) can be easily interpreted when \( f = f(s) \).

Indeed, in this case they simply read as follows:

\[
\lim_{|s| \to \infty} \frac{1}{\log^{3/2}(1 + |s|)} \left| \int_0^1 f(s_0 + \lambda s) d\lambda \right| = 0
\]

uniformly in \( s_0 \in K \) for every compact set \( K \subset \mathbb{R} \).

The arguments in [FZ2] show that this is equivalent to (7) and also to

\[
\lim_{|s| \to \infty} \frac{1}{\log^{3/2}(1 + |s|)} \int_0^1 f(\lambda s) d\lambda = 0.
\]
Remark 1.7. It is proved in [FZ2] that, for each \( \beta > 2 \), there exists a function \( f = f(s) \) satisfying (8) such that the corresponding system (1) is not approximately controllable for all \( T > 0 \). As in the case of null-controllability, for \( f \) satisfying (8) with \( 3/2 \leq \beta \leq 2 \), the approximate controllability of (1) is an open question. \( \square \)

We can establish similar results for (2) under hypotheses of the same kind for \( f \) and \( y_0 \). More precisely, let us introduce the Hilbert space

\[ V = \{ z \in H^1(\Omega) : z = 0 \text{ on } \partial \Omega \setminus \gamma \}. \]

One has the following:

Theorem 1.3. Let \( T > 0 \). Assume that the assumptions in Theorem 1.1 are satisfied. Then (2) is null-controllable at any time \( T > 0 \). \( \square \)

As before, to prove the approximate controllability of (2), we will assume that a global solution in \( C^0([0,T];W^{1,\infty}(\Omega)) \) exists. In other words, we will assume that, for some initial data \( y_0^* \in W^{1,\infty}(\Omega) \cap V \) and some \( v^* \in L^\infty(\gamma \times (0,T)) \), the corresponding system (2) admits a solution \( y^* \in C^0([0,T];W^{1,\infty}(\Omega)) \). In this context, we have the following:

Theorem 1.4. Let \( T > 0 \). Assume that \( f \) is locally Lipschitz-continuous and verifies (9). Also, assume that (2) admits at least one global solution \( y^* \in C^0([0,T];W^{1,\infty}(\Omega)) \) corresponding to the data \( y_0^* \in W^{1,\infty}(\Omega) \cap V \) and \( v^* \in L^\infty(\gamma \times (0,T)) \). Then (2) is approximately controllable at time \( T \). \( \square \)

Remark 1.8. In the proofs of the previous controllability results, we will construct controls satisfying the appropriate properties. These controls are smooth. In particular, they will be such that the associate solutions of (1) and (2) belong to \( C^0([0,T];W^{1,\infty}(\Omega)) \), a space where we can ensure uniqueness. \( \square \)

The rest of this paper is organized as follows. Section §2 is devoted to prove some technical Lemmas we will use below. In §3, we will prove Theorem 1.1. In §4, we will give the proof of the approximate controllability result for system (1), i.e. Theorem 1.2. Finally, in §5, we will sketch the proofs of Theorems 1.3 and 1.4.

2. Some technical results. Before giving the proofs of the Theorems above, we have to present some technical results.

Let us consider the linear problem

\[
\begin{aligned}
\begin{cases}
\Delta y + B \cdot \nabla y + ay = F & \text{in } Q, \\
y = 0 & \text{on } \Sigma, \\
y(x,0) = y_0(x) & \text{in } \Omega,
\end{cases}
\end{aligned}
\]

where \( y_0 \) and \( F \) are given, \( a \in L^\infty(Q) \) and \( B \in L^\infty(Q)^N \). One has the following Lemma, whose proof is given in [LSU]:

Lemma 2.1. Assume that \( F \in L^r(0,T; L^q(\Omega)) \) with

\[
\frac{1}{r} + \frac{N}{2q} < \frac{1}{2}
\]

\( y_0 \in W^{2,p}(\Omega) \cap H^1_0(\Omega) \) with \( p > N, a \in L^\infty(Q) \) and \( B \in L^\infty(Q)^N \). Then the solution \( y \) of (10) verifies

\[
\begin{aligned}
\begin{cases}
y \in L^\infty(0,T; W^{2,\beta}(\Omega)), \quad \partial_t y \in L^r(0,T; L^\beta(\Omega)), \\
\text{with } \quad \beta = \min \left( p, \frac{N}{2} \left( \frac{1}{r} + \frac{N}{2q} \right)^{-1} \right) > N.
\end{cases}
\end{aligned}
\]

\( \square \)
In particular, we see that \( y \in C^0([0, T]; W^{1, \infty}(\Omega)) \). Furthermore, one has

\[
(12) \quad \|y\|_{L^\infty(\Omega; W^{2, p})} + \|\partial y\|_{L^1(\Omega; L^p)} \leq M(\Omega, T, \|a\|_\infty, \|B\|_\infty) \left( \|a_0\|_{W^{2, p}} + \|F\|_{L^1(\Omega; L^p)} \right)
\]

where

\[
(13) \quad M(\Omega, T, \|a\|_\infty, \|B\|_\infty) = \exp \left[ M_0 \left( 1 + T + (T + T^{1/2}) \|a\|_\infty + T \|B\|_\infty^2 \right) \right]
\]

and \( M_0 \) is a positive constant only depending on \( \Omega \).

We will also recall a global Carleman inequality from [1Y] for the linear problem

\[
(14) \quad \begin{cases}
-\partial_t \varphi - \Delta \varphi = F_0 + \sum_{i=1}^N \frac{\partial F_i}{\partial x_i} & \text{in } Q, \\
\varphi = 0 & \text{on } \Sigma, \\
\varphi(x, T) = \varphi_T(x) & \text{in } \Omega,
\end{cases}
\]

where \( F_0, F_i \in L^2(Q) \) (\( 1 \leq i \leq N \)) and \( \varphi_T \in L^2(\Omega) \). One has:

**Lemma 2.2.** There exists a smooth and strictly positive function \( \alpha_0 = \alpha_0(x) \) in \( \overline{\Omega} \) and there exist positive constants \( C_0 \) and \( \sigma_0 \) (only depending on \( \Omega \) and \( \mathcal{O} \)), such that

\[
(15) \quad s^3 \int_Q e^{-2s\sigma_0 t - 3(T - t)^{-3}} |\varphi|^2 \leq C_0 \left( s^3 \int_{\mathcal{O} \times (0, T)} e^{-2s\sigma_0 t - 3(T - t)^{-3}} |\varphi|^2 + \int_Q e^{-2s\sigma_0 t - 2(T - t)^{-2}} |F_0|^2 + s^2 \sum_{i=1}^N \int_Q e^{-2s\sigma_0 t - 2(T - t)^{-2}} |F_i|^2 \right)
\]

for all \( s \geq \sigma_0 = \sigma_0(T + T^2) \), with \( \varphi \) being the solution of (14) associated to \( \varphi_T \in L^2(\Omega) \).

In (15), the function \( \alpha = \alpha(x, t) \) is given by

\[
\alpha(x, t) = \frac{\alpha_0(x)}{t(T - t)}.
\]

**Remark 2.1.** The inequality (15) is based on a similar Carleman inequality for the heat equation with a right hand side in \( L^2(Q) \). The precise way \( \alpha_0 \) depends on \( T \) has been analyzed in [FZ1] and is essential in our analysis.

In the sequel, unless otherwise specified, \( \mathcal{C} \) will stand for a generic positive constant only depending on \( \Omega \) and \( \mathcal{O} \), whose value can change from line to line. Let us introduce the following (adjoint) system

\[
(16) \quad \begin{cases}
-\partial_t q - \Delta q - \nabla \cdot (qB) + aq = 0 & \text{in } Q, \\
q = 0 & \text{on } \Sigma, \\
q(x, T) = q_T(x) & \text{in } \Omega,
\end{cases}
\]

where \( q_T \in L^2(\Omega) \). Arguing as in [FZ1], we can deduce from the Carleman estimates (15) an observability inequality for (16):

**Theorem 2.3.** For any \( a \in L^\infty(\Omega) \), \( B \in L^\infty(\Omega; \mathbb{R}^N) \) and \( q_T \in L^2(\Omega) \), one has:

\[
(17) \quad \|q(\cdot, 0)\|_{L^2}^2 \leq \exp \left[ C \hat{B}(T, \|a\|_\infty, \|B\|_\infty) \int_{\mathcal{O} \times (0, T)} |q|^2 \right]
\]

where \( \hat{B} \) is a positive constant defined in (15) depending only on \( \Omega \) and \( \mathcal{O} \).
with

\[ B(T, \|a\|_\infty, \|B\|_\infty) = \left(1 + \frac{1}{T} + \|a\|_\infty + \|a\|_\infty^{2/3} + (1 + T)\|B\|_\infty^2 \right) \]

where \( q \) is the solution to the corresponding system (16).

**Proof.** Let \( a, B \) and \( \varphi_T \) be given and let \( q \) be the solution to (16). Let us first see that

\[ \frac{s^3}{Q} \int_{Q} e^{-2s \alpha t^{-3}(T-t)^{-3}} |q|^2 \leq C_0 \left( \frac{s^3}{Q} \int_{Q} e^{-2s \alpha t^{-3}} (T-t)^{-3} |q|^2 \right) \]

\[ + \frac{s^3}{Q} \int_{Q} e^{-2s \alpha t^{-3}} |\varphi_t|^2 + \frac{s^3}{Q} \int_{Q} e^{-2s \alpha t^{-3}} (T-t)^{-3} |Bq|^2 \]

for all \( s \geq s_0 \). We can estimate the terms in the right as follows:

\[ \frac{s^3}{Q} \int_{Q} e^{-2s \alpha t^{-3}} |\varphi_t|^2 \leq 2^{-6} T^{-6} \|a\|_\infty^2 \int_{Q} e^{-2s \alpha t^{-3}} (T-t)^{-3} |q|^2, \]

\[ \frac{s^3}{Q} \int_{Q} e^{-2s \alpha t^{-3}} (T-t)^{-3} |Bq|^2 \leq 2^{-2} T^2 \|B\|_\infty^2 \int_{Q} e^{-2s \alpha t^{-3}} (T-t)^{-3} |q|^2. \]

Thus, we deduce from (19) that

\[ \frac{s^3}{Q} \int_{Q} e^{-2s \alpha t^{-3}} (T-t)^{-3} |q|^2 \leq C \int_{Q} e^{-2s \alpha t^{-3}} (T-t)^{-3} |q|^2, \]

provided

\[ s \geq s_1 = \max \left(s_0, 2^{-4/3} C_0^{-1/3} T^2 \|a\|_\infty^{2/3} C_0 T^2 \|B\|_\infty^2 \right). \]

On the other hand, it can be easily verified that

\[ e^{-2s \alpha t^{-3}} (T-t)^{-3} \leq 2^6 T^{-6} \exp (-C_0 T^{-2}) \quad \forall (x, t) \in \overline{Q} \]

and

\[ e^{-2s \alpha t^{-3}} (T-t)^{-3} \geq \left( \frac{16}{3} \right)^3 T^{-6} \exp (-C_0 T^{-2}) \quad \forall (x, t) \in \overline{\Omega} \times [T/4, 3T/4], \]

whenever

\[ s \geq s_2 = \max \left(s_1, 3 T^2 (8 \min_{x \in \Omega} e_0(x))^{-1} \right). \]

Analyzing the structure of the constants \( s_1 \) and \( s_2 \), we see that \( s_2 \leq s_3 \), where \( s_3 \) is of the form

\[ s_3 = \sigma_3 \left( T + T^2 + T^2 \|a\|_\infty^{2/3} + T^2 \|B\|_\infty^2 \right) \]
and \( \sigma_3 \) only depends on \( \Omega \) and \( \mathcal{O} \). From now on, we fix the constant \( s = \sigma_3 \). Taking into account (21) and (22) and coming back to (20) (written for \( s = \sigma_3 \)), we deduce that (18) is satisfied for any solution \( q \) of (16).

Let us now prove that

\[
\|q(\cdot, T/4)\|_2^2 \leq \exp \left[ C \left( \frac{1}{T} + T\|a\|_\infty + T\|B\|_\infty^2 \right) \right] \int_{\Omega \times (T/4, 3T/4)} |q|^2.
\]

Indeed, multiplying (16) by \( q \) and integrating in \( \Omega \), we obtain

\[
- \frac{1}{2} \frac{d}{dt} \int_\Omega |q|^2 \, dx + \int_\Omega |\nabla q|^2 \, dx = - \int_\Omega q B \cdot \nabla q \, dx - \int_\Omega a |q|^2 \, dx \quad \forall t \geq 0.
\]

Thus,

\[
- \frac{d}{dt} \int_\Omega |q|^2 \, dx + \int_\Omega |\nabla q|^2 \, dx \leq (\|B\|_\infty^2 + 2\|a\|_\infty) \int_\Omega |q|^2 \, dx
\]

and

\[
\frac{d}{dt} \left( \exp \left( (2\|a\|_\infty + \|B\|_\infty^2)t \right) \int_\Omega |q|^2 \, dx \right) \geq 0
\]

for all \( t \geq 0 \). Integrating this inequality with respect to time in \([T/4, t]\) with \( t \in [T/4, 3T/4] \), we obtain

\[
\left\{
\begin{array}{c}
\int_\Omega |q(x, t)|^2 \, dx \geq \exp \left[ (2\|a\|_\infty + \|B\|_\infty^2) \left( T/4 - t \right) \right] \int_\Omega |q(x, T/4)|^2 \, dx \\
\geq \exp \left[ - \left( \|a\|_\infty + \frac{1}{2}\|B\|_\infty^2 \right) T \right] \int_\Omega |q(x, T/4)|^2 \, dx
\end{array}
\right.
\]

for all \( t \in [T/4, 3T/4] \). Integrating (25) again with respect to \( t \), we find that

\[
\frac{T}{2} \int_\Omega |q(x, T/4)|^2 \, dx \leq \exp \left[ \left( \|a\|_\infty + \frac{1}{2}\|B\|_\infty^2 \right) T \right] \int_{\Omega \times (T/4, 3T/4)} |q(x, t)|^2.
\]

whence we easily deduce (23).

Finally, let us prove that

\[
\int_\Omega |q(x, 0)|^2 \, dx \leq \exp \left[ C T \left( \|a\|_\infty + \|B\|_\infty^2 \right) \right] \int_\Omega |q(x, T/4)|^2 \, dx.
\]

This, together with (23) and (18) will lead to the desired observability estimate (17).

To prove (27), it suffices to integrate (24) in the time interval \([0, T/4]\). Indeed, we find at once

\[
\int_\Omega |q(x, 0)|^2 \, dx \leq \exp \left[ (2\|a\|_\infty + \|B\|_\infty^2) \frac{T}{4} \right] \int_\Omega |q(x, T/4)|^2 \, dx
\]

and thus (27) holds. This completes the proof of Theorem 2.3. \( \Box \)

In fact, for the analysis of the controllability of the nonlinear problems (1) and (2), we need a refined version of the observability inequality (17). This is furnished by the following result:
Theorem 2.4. For any \( a \in L^\infty(\Omega) \), \( B \in L^\infty(\Omega)^N \) and \( q_T \in L^2(\Omega) \), one has

\[
\|q(\cdot, 0)\|_{L^2}^2 \leq \exp \left[ CK (T, \|a\|_\infty, ||B||_\infty) \left( \int_{\mathcal{O} \times (0, T)} |q| \right)^2 \right],
\]

where

\[
K (T, \|a\|_\infty, ||B||_\infty) = 1 + \frac{1}{T} + T + (T + T^{1/2})||a||_\infty + \|a\|_{\infty}^2 + (1 + T)||B||^2_\infty.
\]

Proof. Let \( \mathcal{O}' \) be a nonempty open set such that \( \mathcal{O}' \subset \subset \mathcal{O} \). From Theorem 2.3 applied to \( \mathcal{O}' \) and the time interval \([T/4, 3T/4]\), we deduce that

\[
\|q(\cdot, T/4)\|_{L^2}^2 \leq \exp \left[ CK'(T, \|a\|_\infty, ||B||_\infty) \int_{\mathcal{O}' \times (T/4, 3T/4)} |q|^2 \right]
\]

where \( q \) is the solution of (16) associated to \( q_T \in L^2(\Omega) \), \( K'(T, \|a\|_\infty, ||B||_\infty) \) is given by

\[
K'(T, \|a\|_\infty, ||B||_\infty) = 1 + \frac{1}{T} + T||a||_\infty + \|a\|_{\infty}^2 + (1 + T)||B||^2_\infty
\]

and \( C \) is a new positive constant, only depending on \( \mathcal{O}' \) (i.e. on \( \mathcal{O} \)) and \( \Omega \). Using (24), we obtain

\[
\int_{\Gamma} |q(x, 0)|^2 \, dx \leq \exp \left( \frac{T}{4} \|a\|_\infty + \|B\|_\infty \right) \int_{\Omega} |q(x, T/4)|^2 \, dx
\]

and combining this with (30), we find that

\[
\|q(\cdot, 0)\|_{L^2}^2 \leq \exp \left[ CK'(T, \|a\|_\infty, ||B||_\infty) \int_{\mathcal{O}' \times (T/4, 3T/4)} |q|^2 \right].
\]

At this point, we are going to use a technical result, related to the regularizing effect of the heat equation, whose proof will be given below:

Lemma 2.5. Let \( \mathcal{O}_i, T_i, r_i \) and \( \gamma_i \) (\( i = 0, 1 \)) be given, with

\[
\begin{align*}
\mathcal{O}' &\subset \subset \mathcal{O}_0 \subset \subset \mathcal{O}_1 \subset \subset \mathcal{O}, \quad 0 \leq T_1 < T_0 < T/2, \quad 1 \leq r_1 < r_0 < \infty, \\
1 \leq \gamma_1 < \gamma_0 < \infty, \quad &\frac{1}{\gamma_1} + \frac{1}{\gamma_0} + \frac{N}{2} \left( \frac{1}{r_1} - \frac{1}{r_0} \right) < \frac{1}{2}.
\end{align*}
\]

Then

\[
\left( \int_{T_0}^{T-T_0} \left( \int_{\mathcal{O}_0} \left| q \right|^{\gamma_0} \, dx \right)^\frac{\gamma_0}{\gamma_0 - 1} \, dt \right)^\frac{1}{\gamma_0 - 1} \leq C T^\lambda H(T, \|a\|_\infty, ||B||_\infty) \left( \int_{T_1}^{T-T_1} \left( \int_{\mathcal{O}_1} \left| q \right|^\gamma \, dx \right)^\frac{\gamma}{\gamma - 1} \, dt \right)^\frac{1}{\gamma - 1}
\]

for all \( q_T \in L^2(\Omega) \), with \( C = C(\mathcal{O}_0, \mathcal{O}_1, r_i, \gamma_i, N) \), \( \lambda = \lambda(r_i, \gamma_i, N) \) and

\[
H(T, \|a\|_\infty, ||B||_\infty) = 1 + \frac{T^{1/2}}{T_0 - T_1} + T^{1/2}(1 + \|a\|_\infty) + (1 + T^{1/2})||B||_\infty.
\]

We will now apply this Lemma together with (31). To this end, let us set $r_0 = \gamma_0 = 2$ and let us introduce the numbers $\gamma_i$ and $r_i$, given by the equalities

$$\frac{1}{\gamma_i} = \frac{1}{r_i} = \frac{i}{2(N + 2)}, \quad 1 \leq i \leq N + 2.$$

It is immediate that $\gamma_{N+1}, r_{N+1} > 1$ and $\gamma_{N+2} = r_{N+2} = 1$. Now, let us set $\delta = T/4(N + 2)$. Accordingly,

$$[T/4 - (N + 2)\delta, 3T/4 + (N + 2)\delta] = [0, T].$$

Let us also introduce a family of open sets $O_i$ such that

$$O^I = O_0 \subseteq O_1 \subseteq O_2 \subseteq \ldots \subseteq O_N + 1 \subseteq O_{N+2} = O.$$

For $0 \leq i \leq N + 1$, we can use inequality (32) with $O_0$, $O_i$, $T_0$, $T_1$, $r_0$, $r_1$, $\gamma_0$ and $\gamma_1$ respectively replaced by $O_i$, $O_{i+1}$, $T/4 - i\delta$, $T/4 - (i + 1)\delta$, $r_i$, $r_{i+1}$, $\gamma_i$ and $\gamma_{i+1}$. The whole set of these inequalities gives

$$\left( \int_{\bigcup_{i=0}^N (T/4, 3T/4)} |v|^2 \right)^{1/2} \leq C T^\alpha H(T, ||a||_\infty, ||B||_\infty)^2 \left( \int_{\bigcup_{i=0}^N (0, T)} |v|^2 \right),$$

where $\beta = N + 2$ and $\alpha$ is the sum of the exponents $\lambda_i$. If we now combine the inequalities (31) and (34), we obtain (28). This completes the proof of Theorem 2.4.

Proof of Lemma 2.5. Let $\rho_1$ and $\rho_2$ be functions in $D(O_1)$ and $D((T_1, T - T_1))$ respectively such that

$$\rho_1 \equiv 1 \text{ in } O_0, \quad \rho_2 \equiv 1 \text{ in } (T_0, T - T_0)$$

and $0 \leq \rho_1, \rho_2 \leq 1$. Let us put $\rho(x, t) = \rho_1(x)\rho_2(t)$ and $u = \rho q$, with $q$ being the solution to (16) associated to $q_T \in L^2(\Omega)$. Obviously,

$$\text{supp } u \subset O_1 \times (T_1, T - T_1)$$

and

$$\begin{cases}
\begin{align*}
\partial_t u - \Delta u &= -\alpha \rho q + \nabla \cdot (\rho q B) - (\partial_t \rho + \Delta \rho) q = -2\nabla \rho \cdot \nabla q - (\nabla \rho \cdot B) q \quad &\text{in } Q, \\
u &= 0 \quad &\text{on } \Sigma, \\
u(x, T) &= 0 \quad &\text{in } \Omega.
\end{align*}
\end{cases}$$

In order to clarify the computations, let us put $\tilde{u}(x, t) = u(x, T - t)$ for $(x, t) \in Q$. In a similar way, let us introduce the functions $\tilde{\alpha}$, $\tilde{B}$, $\tilde{\rho}$ and $\tilde{q}$. We then have

$$\begin{cases}
\begin{align*}
\partial_t \tilde{\alpha} - \Delta \tilde{\alpha} &= F \quad &\text{in } Q, \\
\tilde{\alpha} &= 0 \quad &\text{on } \Sigma, \\
\tilde{\alpha}(x, 0) &= 0 \quad &\text{in } \Omega.
\end{align*}
\end{cases}$$

and $F$ is given by

$$F = -\tilde{\alpha} \rho \tilde{q} + \nabla \cdot (\rho \tilde{q} \tilde{B}) - (\partial_t \tilde{\rho} + \Delta \tilde{\rho}) \tilde{q} = -2\nabla \tilde{\rho} \cdot \nabla \tilde{q} - (\nabla \tilde{\rho} \cdot \tilde{B}) \tilde{q}.$$
Let us denote by \( \{ S(t) : t \geq 0 \} \) the semigroup generated by the heat equation with Dirichlet boundary conditions. Then one has

\[
\tilde{u}(\cdot, t) = \int_0^t S(t - s) F(\cdot, s) \, ds,
\]

where the integral can be understood, for instance, in \( L^{\infty}(\Omega) \).

Thanks to the regularizing effect of the heat equation, taking \( L^{\infty}\)-norms in (35), we obtain the following for \( t \in (T_1, T - T_1) \):

\[
\| \tilde{u}(\cdot, t) \|_{L^{\infty}} \leq C \left( \| B \|_{\infty} + 1 \right) \int_{T_1}^t (t - s)^{-\frac{3}{2} \left( \frac{1}{r_1} - \frac{1}{r_0} \right)} \| \tilde{q}(\cdot, s) \|_{L^{r_1}(\Omega)} \, ds
\]

\[
+ \left( 1 + \frac{T_0 - T_1}{T_0 - T_1} + \| a \|_{\infty} + \| B \|_{\infty} \right) \int_{T_1}^t (t - s)^{-\frac{3}{2} \left( \frac{1}{r_1} - \frac{1}{r_0} \right)} \| \tilde{q}(\cdot, s) \|_{L^{r_1}(\Omega)} \, ds,
\]

Here, \( C \) is a positive constant depending on \( C_0 \) and \( \mathcal{O}_1 \). This gives

\[
\| \tilde{u}(\cdot, t) \|_{L^{\infty}} \leq CH \int_{T_1}^t (t - s)^{-\frac{3}{2} \left( \frac{1}{r_1} - \frac{1}{r_0} \right)} \| \tilde{q}(\cdot, s) \|_{L^{r_1}(\Omega)} \, ds
\]

for all \( t \in (T_1, T - T_1) \), where \( H = H(T, \| a \|_{\infty}, \| B \|_{\infty}) \) is given by (33). Due to the assumption

\[
\frac{N}{2} \left( \frac{1}{r_1} - \frac{1}{r_0} \right) + \frac{1}{\gamma_1} - \frac{1}{\gamma_0} < \frac{1}{2}
\]

we can apply Young’s inequality to (37) and estimate the \( L^{\infty}(0, T; L^{r_0}(\Omega)) \)-norm of \( \tilde{u} \) as follows

\[
\left( \int_{T_1}^{T - T_1} \| \tilde{u}(\cdot, t) \|_{L^{r_0}}^\gamma \, dt \right)^{1/\gamma_0} \leq C H T^\lambda \left( \int_{T_1}^{T - T_1} \| \tilde{q}(\cdot, t) \|_{L^{r_1}(\Omega)}^\gamma \, dt \right)^{1/\gamma_1}
\]

Here, \( C \) is a new positive constant only depending on \( \Omega, \mathcal{O}_1, r_i, \gamma_i \) and \( N \) and \( \lambda \) are given by (33) and

\[
\lambda = - \left[ \frac{N}{2} \left( \frac{1}{r_1} - \frac{1}{r_0} \right) + \frac{1}{\gamma_1} - \frac{1}{\gamma_0} \right] + \frac{1}{2}.
\]

Inequality (32) is directly obtained from (38). This completes the proof of Lemma 2.5. \( \Box \)

\textbf{Remark 2.2.} As an easy consequence of Theorem 2.4 and (28), we can also deduce for each \( r \in (1, \infty) \) an observability inequality in \( L^r(\Omega \times (0, T)) \):

\[
\| q(\cdot, 0) \|_{L^2}^2 \leq \exp \left[ C_r K(T, \| a \|_{\infty}, \| B \|_{\infty}) \left( \int_{\mathcal{O} \times (0, T)} |q|^r \right)^{\frac{1}{r}} \right]
\]

for any \( a \in L^\infty(\Omega), B \in L^\infty(\Omega)^N \) and \( q_T \in L^2(\Omega) \). In (39), \( K(T, \| a \|_{\infty}, \| B \|_{\infty}) \) is given by (29) and \( C_r \) only depends on \( \Omega, \mathcal{O} \) and \( r \). \( \Box \)
3. Proof of the null controllability result. This section is devoted to prove Theorem 1.1. Using Theorem 2.4, we will first prove a null controllability result for a similar linear heat equation with controls in $L^\infty(\mathcal{O} \times [0, T])$. We will then apply a fixed point argument to obtain the desired result. The structure of the proof (the controllability of a similar linear system + a fixed point argument) is rather general. It was introduced in [Z], in the context of the boundary controllability of the semilinear wave equation. For other results proved in a similar way, see for instance [FPZ] and [FI].

3.1. A null controllability result for a linear problem. We will consider the linear system

\[
\begin{cases}
\partial_t y - \Delta y + B \cdot \nabla y + ay = v1_{\mathcal{O}} & \text{in } Q, \\
y(x, 0) = y_0(x) & \text{on } \Sigma, \\
y(x, T) = 0 & \text{in } \Omega,
\end{cases}
\]

where $a \in L^\infty(Q)$, $B \in L^\infty(Q)^N$ and $y_0 \in L^2(\Omega)$ are given. The following holds:

**Theorem 3.1.** Assume that $T > 0$, $a \in L^\infty(Q)$, $B \in L^\infty(Q)^N$ and $y_0 \in L^2(\Omega)$. Then there exists a control $\tilde{v} \in L^\infty(\mathcal{O} \times [0, T])$ such that the corresponding solution of (40) satisfies

\[
\tilde{y}(x, T) = 0 \quad \text{in } \Omega.
\]

Furthermore, $\tilde{v}$ can be chosen in such a way that

\[
\|\tilde{v}\|_{L^\infty(\mathcal{O} \times [0, T])} \leq \exp \left[ C K(T, \|a\|_\infty, \|B\|_\infty, \|y_0\|_{L^2}) \right].
\]

where $K(T, \|a\|_\infty, \|B\|_\infty)$ is given by (29).

**Proof.** For every $\varepsilon > 0$, let us consider the functional $J_\varepsilon$, with

\[
J_\varepsilon(q_T) = \frac{1}{2} \left( \int_{\mathcal{O} \times (0, T)} |q|^2 + \varepsilon \|q_T\|_{L^2}^2 + \int_\Omega q(x, 0) y_0(x) \, dx \right) \quad \forall q_T \in L^2(\Omega).
\]

Here, $q$ is the solution of (16) associated to $q_T \in L^2(\Omega)$. It is easy to see that $J_\varepsilon$ is a continuous and strictly convex functional in $L^2(\Omega)$. Furthermore, from (20), it is immediate to deduce the following unique continuation property for (16): If $q \equiv 0$ in $\mathcal{O} \times [0, T]$, then $q \equiv 0$. Thus, arguing as in [FPZ], we also see that

\[
\liminf_{\|q_T\|_{L^2} \to \infty} \frac{J_\varepsilon(q_T)}{\|q_T\|_{L^2}^2} \geq \varepsilon
\]

and, therefore, $J_\varepsilon$ achieves its minimum at a unique point $q_T, x \in L^2(\Omega)$.

Let $\tilde{q}_T$ be the solution of (16) associated to $q_T, x \in L^2(\Omega)$. Taking $v = \tilde{v}_T$ in (40) with

\[
\tilde{v}_T = \left( \frac{\text{sgn}\tilde{q}_T (\int_{\mathcal{O} \times (0, T)} |\tilde{q}_T|) 1_{\mathcal{O}}} \right)
\]

and arguing as in [FPZ], we see that the associate solution $\tilde{y}_T$ satisfies

\[
\|\tilde{y}_T(\cdot, T)\|_{L^2} \leq \varepsilon.
\]
It is not difficult to see that
\begin{equation}
\|\hat{v}_e\|_{L^\infty(\mathcal{O} \times (0, T))} = \int_{\mathcal{O} \times (0, T)} |\hat{v}_e| \leq \exp[CK(T, \|a\|_{\infty}, \|B\|_{\infty})] \|y_0\|_{L^2}
\end{equation}
for all \( \varepsilon > 0 \). Indeed, the fact that
\[\|\hat{v}_e\|_{L^\infty(\mathcal{O} \times (0, T))} = \int_{\mathcal{O} \times (0, T)} |\hat{v}_e|\]
is implied by (44). On the other hand, since
\[J_e(\hat{q}_{T, e}) \leq J_e(0) = 0,\]
we see from (43) that
\[\frac{1}{2} \left( \int_{\mathcal{O} \times (0, T)} |\hat{v}_e|^2 \right) \leq -\int_{\Omega} \hat{v}_e(x, 0) y_0(x) \, dx \leq \|\hat{v}_e(\cdot, 0)\|_{L^2} \|y_0\|_{L^2}.
\]
In view of (28), (46) holds.

Since \( \hat{v}_e \) is uniformly bounded in \( L^\infty(\mathcal{O} \times (0, T)) \), for an appropriate subsequence, we must have
\begin{equation}
\hat{v}_e \rightharpoonup \hat{v} \text{ weakly-\( \ast \) in } L^\infty(\mathcal{O} \times (0, T)),
\end{equation}
where \( \hat{v} \in L^\infty(\mathcal{O} \times (0, T)) \) and satisfies (42). Accordingly,
\[\hat{y}_e(T) \rightharpoonup \hat{y}(T) \text{ in } L^2(\Omega),\]
where \( \hat{y} \) is the solution of (40) associated to \( \hat{v} \). Since we have (45) for all \( \varepsilon > 0 \), (41) is satisfied. This ends the proof. \( \square \)

3.2. Proof of Theorem 1.1. We are now ready to prove Theorem 1.1. First, observe that we can assume in this Theorem that \( y_0 \in W^{2, p}(\Omega) \cap H^1_0(\Omega) \), with \( p > N \). Indeed, it suffices to set \( v = 0 \) for \( t \in [0, \delta] \) and to work in the time interval \([\delta, T] \), looking at \( y(\cdot, \delta) \) as the initial state. As we said above, a fixed point argument will be used. For convenience, it will be assumed in a first step that \( g \) and \( G \) are continuous.

3.2.1. The case in which \( g \) and \( G \) are continuous. Let \( y_0 \) be given in \( W^{2, p}(\Omega) \cap H^1_0(\Omega) \) with \( p > N \). We will assume that
\begin{equation}
g \in C^0(\mathbb{R} \times \mathbb{R}^N), \quad G \in C^0(\mathbb{R} \times \mathbb{R}^N)^N
\end{equation}
and (6) is satisfied. It is then clear that, for each \( \varepsilon > 0 \), there exists \( C_\varepsilon > 0 \) such that
\begin{equation}
|g(s, p)|^{2/3} + |G(s, p)|^2 \leq C_\varepsilon + \varepsilon \log(1 + |s| + |p|) \quad \forall (s, p) \in \mathbb{R} \times \mathbb{R}^N.
\end{equation}

Let us set \( Z = C^0([0, T]; W^{1, \infty}(\Omega)) \) and let \( R > 0 \) be a constant whose value will be determined below. We will use the truncation functions \( T_R : \mathbb{R} \rightarrow \mathbb{R} \) and \( T_R : \mathbb{R}^N \rightarrow \mathbb{R}^N \), which are given as follows:
\[T_R(s) = \begin{cases} s & \text{if } |s| \leq R, \\ R \text{sgn}(s) & \text{otherwise.} \end{cases}\]
and
\[ T_R(p) = (T_R(p_i))_{1 \leq i \leq N}, \quad \forall p \in \mathbb{R}^N. \]

For each \( z \in Z \), we will consider the corresponding linear systems
\[
\begin{cases}
\partial_y u - \Delta y + G(T_R(z), T_R(\nabla z)) \cdot \nabla y + g(T_R(z), T_R(\nabla z)) y = v 1_\Omega & \text{in } Q, \\
y(x, 0) = y_0(x) & \text{in } \Omega.
\end{cases}
\]

We are going to associate to \( z \) a family \( U(z) \) of \( L^\infty \)-controls which serve to drive the solutions to zero. Observe that (50) is of the form (40) with
\[
\begin{cases}
\alpha = a_z = g(T_R(z), T_R(\nabla z)) \in L^\infty(Q), \\
B = B_z = G(T_R(z), T_R(\nabla z)) \in L^\infty(Q)^N.
\end{cases}
\]

Consequently, we can apply Theorem 3.1 to (50). In fact, we are going to apply this result in an adequate (eventually smaller) time interval \((0, T_z]\), where
\[
(52) \quad T_z = \min \left\{ T, \| g(T_R(z), T_R(\nabla z)) \|_{L^\infty}^{2/3}, \| g(T_R(z), T_R(\nabla z)) \|_{L^\infty}^{-1/3} \right\}.
\]

This is a key point in our proof that will lead to appropriate estimates (this idea is taken from [FZ2]).

From Theorem 3.1, we directly deduce the existence of a control \( \tilde{u}_z \in L^\infty(O \times (0, T_z]) \) such that the solution of (50) in \( \Omega \times (0, T_z] \) with \( v = \tilde{u}_z \) satisfies
\[
\tilde{u}_z(x, T_z) = 0 \quad \text{in } \Omega
\]
and, moreover,
\[
\| \tilde{u}_z \|_{L^\infty(O \times (0, T_z])} \leq \exp \left[ C K(T_z, \| a_z \|_{L^\infty}, \| B_z \|_{L^\infty}) \| y_0 \|_{L^2} \right]
\]
\((K \text{ is given by } (29) \text{ and } a_z \text{ and } B_z \text{ are given by } (51)).

Let \( \tilde{v}_z \) and \( \tilde{u}_z \) be the extensions by zero of \( \tilde{v}_z \) and \( \tilde{u}_z \) to the whole cylinder \( Q = \Omega \times (0, T) \). It is clear that \( \tilde{u}_z \) is the corresponding solution of (50) associated to \( \tilde{v}_z \) and
\[
(53) \quad \tilde{u}_z(x, T) = 0 \quad \text{in } \Omega.
\]

From the definition of \( T_z \), we see that
\[
(54) \quad \| \tilde{u}_z \|_{L^\infty(O \times (0, T_z])} \leq \exp \left[ C \left( 1 + \| a_z \|_{L^\infty}^{2/3} + \| B_z \|_{L^\infty}^{2/3} \right) \| y_0 \|_{L^2} \right],
\]
where the positive constant \( C \) now depends on \( \Omega, O \) and \( T \).

On the other hand, from (48) and Lemma 2.1, we obtain that
\[
\tilde{u}_z \in C^0([0, T_z]; W^{1, \infty}(\Omega))
\]
and
\[
\| \tilde{u}_z \|_{C^0([0, T_z]; W^{1, \infty}(\Omega))} \leq M(\Omega, T_z, \| a_z \|_{L^\infty}, \| B_z \|_{L^\infty})(\| y_0 \|_{W^{2,p}} + \| \tilde{v}_z \|_{L^\infty(O \times (0, T_z])}).
\]
\((M\) is given by (13)). Taking again into account the definition of \(T_z\), the estimate (54) and the definition of \(\tilde{y}_z\), we find that \(\tilde{y}_z \in Z\) and

\[
||\tilde{y}_z||_Z \leq \exp \left[ C \left( 1 + ||\alpha_z||_{\infty}^{2/3} + ||B_z||_{\infty}^{2/3} \right) \right] ||y_0||_{W^{2,p}}
\]

where (again) \(C = C(\Omega, \mathcal{O}, T)\).

The estimates (54) and (55) can be written in the form

\[
||\tilde{y}_z||_{L^\infty(\mathcal{O} \times (0,T))} \leq C_1(\Omega, \mathcal{O}, T, z)||y_0||_{L^2}
\]

and

\[
||\tilde{y}_z||_Z \leq C_1(\Omega, \mathcal{O}, T, z)||y_0||_{W^{2,p}}
\]

where

\[
C_1(\Omega, \mathcal{O}, T, z) = \exp \left[ C \left( 1 + ||\alpha_z||_{\infty}^{2/3} + ||B_z||_{\infty}^{2/3} \right) \right].
\]

For any given \(v \in L^\infty(\mathcal{O} \times (0,T))\), let \(y_v \in Z\) be the solution of (50) in \(Q\) with right hand side \(v\) (in order to simplify the notation, we omit the dependence on \(z\)). With this notation in mind, let us now set for each \(z \in Z\)

\[
U(z) = \{ v \in L^\infty(\mathcal{O} \times (0,T)) : y_v(T) = 0, \quad ||v||_{L^\infty(\mathcal{O} \times (0,T))} \leq C_1(\Omega, \mathcal{O}, T, z)||y_0||_{L^2} \}
\]

and

\[
\Lambda(z) = \{ y_v : v \in U(z), \quad ||y_v||_Z \leq C_1(\Omega, \mathcal{O}, T, z)||y_0||_{W^{2,p}} \}.
\]

In this way, we have been able to introduce a set-valued mapping on \(Z\)

\[
z \mapsto \Lambda(z).
\]

We will prove that this mapping possesses at least one fixed point \(y\). We will also prove that, for some \(R\), every fixed point of \(\Lambda\) verifies

\[
||y||_Z \leq R.
\]

Of course, this will imply the existence of a control \(v \in L^\infty(\mathcal{O} \times (0,T))\) such that (1) has a solution satisfying (3).

Let us see that Kakutani’s Fixed Point Theorem can be applied to \(\Lambda\). First, from (56) and (57), we deduce that \(\Lambda(z)\) is, for every \(z \in Z\), a nonempty set. Moreover, it is easy to check that \(\Lambda(z)\) is a uniformly bounded closed convex subset of \(Z\). Owing to the regularity hypothesis on \(y_0\) and Lemma 2.1, we have (11) (here \(\beta = p\)) and the estimate

\[
||y||_{L^\infty(W^{2,p})} + ||\partial_y||_{L^\infty(L^p)} \leq C(\Omega, \mathcal{O}, T, R, ||y_0||_{W^{2,p}}),
\]

(where \(C(\Omega, \mathcal{O}, T, R, ||y_0||_{W^{2,p}})\) is independent of \(z\)) for any \(y \in \Lambda(z)\). Since \(p > N\), we can apply well known compactness results and conclude that there exists a compact set \(K \subset Z\) (which depends on \(R\)) such that

\[
\Lambda(z) \subset K \quad \forall z \in Z
\]
(for instance, see [S]).

Let us now prove that the mapping \( z \mapsto \Lambda(z) \) is upper hemicontinuous, i.e. that the real-valued function

\[
z \in Z \mapsto \sup_{y \in \Lambda(z)} \langle \mu, y \rangle
\]

is upper semicontinuous for each bounded linear form \( \mu \in Z' \). In other words, let us see that

\[
B_{\alpha, \mu} = \{ z \in Z : \sup_{y \in \Lambda(z)} \langle \mu, y \rangle \geq \alpha \}
\]

is a closed set of \( Z \) for every \( \alpha \in \mathbb{R} \) and every \( \mu \in Z' \). Thus, let \( \{ z_n \} \) be a sequence in \( B_{\alpha, \mu} \) such that

\[
z_n \to z \quad \text{in} \quad Z.
\]

Our aim is to prove that \( z \in B_{\alpha, \mu} \). In view of the continuity hypothesis on \( g \) and \( G \), we have

\[
g(T_R(z_n), \nabla z_n) \to g(T_R(z), \nabla z) \quad \text{in} \quad L^\infty(Q),
\]

and

\[
G(T_R(z_n), \nabla z_n) \to G(T_R(z), \nabla z) \quad \text{in} \quad L^\infty(Q)^N.
\]

Since all sets \( \Lambda(z_n) \) are compact and satisfy (61), we deduce that

\[
(62) \quad \alpha \leq \sup_{y \in \Lambda(z_n)} \langle \mu, y \rangle = \langle \mu, y_n \rangle
\]

for some \( y_n \in \Lambda(z_n) \). From the definitions of \( \Lambda(z_n) \) and \( U(z_n) \), there must exist \( v_n \in L^\infty(O \times (0, T)) \) such that

\[
\partial_t y_n - \Delta y_n + G(T_R(z_n), \nabla z_n) \cdot \nabla y_n + g(T_R(z_n), \nabla z_n) y_n = v_n I_O \quad \text{in} \quad Q.
\]

Furthermore,

\[
\|v_n\|_{L^\infty(O \times (0, T))} \leq C_1(\Omega, O, T, z_n) \|y_n\|_{L^2}
\]

and

\[
\|y_n\|_Z \leq C_1(\Omega, O, T, z_n) \|y_0\|_{W^{2,p}},
\]

whence \( y_n \) (resp. \( v_n \)) is uniformly bounded in \( Z \) (resp. \( L^\infty(O \times (0, T)) \)). Therefore, we must write the following at least for a subsequence:

\[
y_n \to \tilde{y} \quad \text{strongly in} \quad Z
\]

(recall that (61) is satisfied) and

\[
v_n \rightharpoonup \tilde{v} \quad \text{weakly-* in} \quad L^\infty(O \times (0, T)).
\]
Now, it is not difficult to check that

\[
\begin{aligned}
\begin{cases}
\partial_t \tilde{y} - \Delta \tilde{y} + G(T_R(z), \mathbf{T}_R(\nabla z)) \cdot \nabla \tilde{y} + g(T_R(z), \mathbf{T}_R(\nabla z)) \tilde{y} = \tilde{\alpha} \mathbb{1}_\Omega & \text{in } Q, \\
\tilde{y} = 0 & \text{on } \Sigma, \\
\tilde{y}(x, 0) = y_0(x), & \tilde{y}(x, T) = 0 & \text{in } \Omega,
\end{cases}
\end{aligned}
\]

i.e. that \(\tilde{\alpha} \in U(z)\) and \(\tilde{y} \in \Lambda(z)\). Consequently, we can take limits in (62) and deduce that

\[
\alpha \leq \langle \mu, \tilde{y} \rangle \leq \sup_{y \in \Lambda(z)} \langle \mu, y \rangle,
\]

this is to say, \(z \in B_{\alpha, R}\). This proves that \(z \mapsto \Lambda(z)\) is upper hemicontinuous.

As a consequence, for any fixed \(R > 0\), Kakutani’s Theorem can be applied ensuring the existence of a fixed point of \(\Lambda\). As we said above, we will finish the proof by showing that we can choose \(R > 0\) in such a way that any fixed point of \(\Lambda\) satisfies (60). It is just here where the assumptions (6) (in fact (49)) will be used.

Thus, let \(y\) be a fixed point of \(\Lambda\) associated to the control \(v \in U(y)\). Then (57), (58), (49), and (49) lead to the estimates

\[
\|y\|_Z \leq \exp \left( C \left( 1 + ||g(T_R(y), \mathbf{T}_R(\nabla y))||_\infty^2 + ||G(T_R(y), \mathbf{T}_R(\nabla y))||_\infty^2 \right) \right) ||y_0||_{W^{2,p}}
\]

\[
\leq \exp (C (1 + C_\varepsilon + \varepsilon \log (1 + 2R))) ||y_0||_{W^{2,p}}
\]

\[
= \exp (C (1 + C_\varepsilon)) (1 + 2R)^C ||y_0||_{W^{2,p}}
\]

where \(C = C(\Omega, \mathcal{O}, T)\). Taking \(\varepsilon = 1/(2C)\), we find that

\[
\|y\|_Z \leq C(1 + 2R)^{1/2} ||y_0||_{W^{2,p}},
\]

whence (60) holds whenever \(R\) is large enough (depending on \(\Omega, \mathcal{O}, T, g\), and \(G\)). We have then proved Theorem 1.1 in the case of smooth data.

### 3.2.2. The general case

Let us now suppose that \(f\) is a locally Lipschitz-continuous function satisfying assumption (5) (with \(f(0,0) = 0\) and (6). Let us introduce a function \(\rho \in \mathcal{D}(\mathbb{R} \times \mathbb{R}^N)\) such that \(\rho \geq 0\) in \(\mathbb{R} \times \mathbb{R}^N\), \(\text{supp } \rho \subset \overline{B}(0,1)\) and

\[
\int_{\mathbb{R} \times \mathbb{R}^N} \rho(s, p) \, ds \, dp = 1.
\]

We consider the functions \(\rho_n, g_n\), and \(G_n\) \((n \geq 1)\), with

\[
\rho_n(s, p) = \frac{1}{n^{N+1}} \rho(ns, np) \quad \forall (s, p) \in \mathbb{R} \times \mathbb{R}^N,
\]

\[
g_n = \rho_n * g, \quad G_n = \rho_n * G.
\]

Then it is not difficult to check that the following properties of \(g_n\) and \(G_n\) hold:

1. \(g_n \in C^0(\mathbb{R} \times \mathbb{R}^N)\) and \(G_n \in C^0(\mathbb{R} \times \mathbb{R}^N)^N\) \(\forall n \geq 1\).
2. If we put \(f_n(s, p) = g_n(s, p)s + G_n(s, p) \cdot p\) for all \((s, p) \in \mathbb{R} \times \mathbb{R}^N\), then

\[
f_n \to f \quad \text{uniformly in the compact sets of } \mathbb{R} \times \mathbb{R}^N.
\]
3. For any given $M > 0$, there exists $C(M) > 0$ such that
\[
\sup_{|s-p| \leq M} (|g_n(s, p)| + |G_n(s, p)|) \leq C(M) \quad \forall n \geq 1.
\]

4. The functions $g_n$ and $G_n$ verify (6) uniformly in $n$, that is to say, for any $\varepsilon > 0$, there exists $M(\varepsilon) > 0$ such that
\[
\begin{align*}
|g_n(s, p)| & \leq \varepsilon \log^{3/2}(1 + |s| + |p|), \\
|G_n(s, p)| & \leq \varepsilon \log^{1/2}(1 + |s| + |p|),
\end{align*}
\]
whenever $|(s, p)| \geq M(\varepsilon)$ for all $n \geq 1$.

For every $n$, we can argue as in §3.2.1 and find a control $\nu_n \in L^\infty(\Omega \times (0, T))$ such that the system
\[
\begin{aligned}
\partial_t y_n - \Delta y_n + f_n(y_n, \nabla y_n) &= \nu_n 1_{\Omega} \quad \text{in } Q, \\
\partial_t y_n &= 0 \quad \text{on } \Sigma, \\
y_n(x, 0) &= y_0(x) \quad \text{in } \Omega,
\end{aligned}
\]
possesses at least one solution $y_n \in Z$ satisfying
\[
y_n(x, T) = 0 \quad \text{in } \Omega.
\]
From the properties satisfied by $g_n$ and $G_n$ and thanks to the estimates obtained in §3.2.1, we deduce that
\[
\|\nu_n\|_{L^\infty(\Omega \times (0, T))} \leq C, \quad \|y_n\|_{Z} \leq C \quad \forall n \geq 1.
\]
In fact, Lemma 2.1 allows to write that $y_n \in K$ for all $n$, with $K$ being a fixed compact set in $Z$. Accordingly, we can assume that, at least for a subsequence,
\[
\nu_n \to \nu \text{ weakly-}* \text{ in } L^\infty(\Omega \times (0, T)),
\]
\[
y_n \to y \text{ strongly in } Z.
\]
Hence, passing to the limit in (64), we find a control $\nu \in L^\infty(\Omega \times (0, T))$ such that (1) possesses a solution $y$ satisfying (3). This ends the proof of Theorem 1.1. \qed

Remark 3.1. Analyzing the proof of Theorem 1.1, we deduce that the null controllability result remains valid if we change (6) by the following assumptions:
\[
\limsup_{|(s, p)| \to \infty} \frac{|g(s, p)|}{\log^{3/2}(1 + |s| + |p|)} \leq l_1 < \infty, \quad \limsup_{|(s, p)| \to \infty} \frac{|G(s, p)|}{\log^{1/2}(1 + |s| + |p|)} \leq l_2 < \infty,
\]
where $l_1$ and $l_2$ are positive and sufficiently small (only depending on $\Omega$ and $Q$). \qed

Remark 3.2. In Theorem 1.1, we can consider as well a more general nonlinear term of the form $f(x, t; s, p)$, with $(x, t) \in Q$ and $(s, p) \in \mathbb{R} \times \mathbb{R}^N$. The assumptions on $f$ have to be the following in this case:
1. $f(x, t; 0, 0) = 0 \quad \forall (x, t) \in Q$,
2. $f(\cdot; s, p) \in L^\infty(Q) \quad \forall (s, p) \in \mathbb{R} \times \mathbb{R}^N$,
3. $f(x, t; \cdot)$ is locally Lipschitz-continuous for $(x, t)$ a.e. in $Q$ with Lipschitz constants independent of $(x, t)$ in the bounded sets of $\mathbb{R} \times \mathbb{R}^N$. 

\[\]
4. $f(\cdot, s, p) = g(\cdot, s, p) + G(\cdot, s, p) \cdot p$ for all $(s, p) \in \mathbb{R} \times \mathbb{R}^N$, with
\[
\lim_{|(s, p)| \to \infty} \frac{|g(x, t, s, p)|}{\log^{1/2} (1 + |s| + |p|)} = 0, \quad \lim_{|(s, p)| \to \infty} \frac{|G(x, t, s, p)|}{\log^{1/2} (1 + |s| + |p|)} = 0
\]
uniformly in $(x, t) \in Q$. \[\qed\]

Remark 3.3. Adapting the arguments used in the proof of Theorem 1.1, we can deduce a local null controllability result for (1) with a general nonlinear term $f(s, p)$ satisfying $f(0, 0) = 0$. To be precise, if $f$ is given, there exists $\delta = \delta(\Omega, Q, T, f) > 0$, such that, for every $y_0 \in W^{2,p}(\Omega) \cap H_0^1(\Omega)$ ($p > N$) with $\|y_0\|_{W^{2,p}} \leq \delta$, a control $v \in L^\infty(Q \times (0, T))$ can be found such that the corresponding problem has a unique solution $y \in L^\infty(0, T; W^{1,\infty}(\Omega))$ which satisfies
\[
y(x, T) = 0 \quad \text{in} \quad \Omega. \[\qed\]

4. Proof of the approximate controllability result. In this Section we will prove Theorem 1.2. Let us fix $T > 0$, $\varepsilon > 0$, $y_0 \in W^{1,\infty}(\Omega) \cap H_0^1(\Omega)$ and $y_d \in W^{2,p}(\Omega) \cap H_0^1(\Omega)$ with $p > N$ (for instance). Obviously, it will be sufficient to consider final data in $W^{2,p}(\Omega) \cap H_0^1(\Omega)$, since this space is dense in $L^2(\Omega)$.

Recall that we are in the range of nonlinearities for which blow-up may occur. This is why we will have to assume that a global solution $y^* \in C^0([0, T]; W^{1,\infty}(\Omega))$ exists. This hypothesis, together with (9), will yield the desired approximate controllability property. We will present the proof in several steps and we will start with a result concerning the exact controllability to the trajectories in $C^0([0, T]; W^{1,\infty}(\Omega))$.

Lemma 4.1. Assume the hypotheses on $f$ in Theorem 1.2 are satisfied. Let $y^*$ be a solution to (1) in $C^0([0, T]; W^{1,\infty}(\Omega))$, corresponding to the data
\[
y_0^* \in W^{1,\infty}(\Omega) \cap H_0^1(\Omega), \quad v^* \in L^\infty(\Omega \times (0, T)).
\]

There exists a control $v \in L^\infty(\Omega \times (0, T))$ and a state $y \in C^0([0, T]; W^{1,\infty}(\Omega))$ such that
\[
y(x, T) = y^*(x, T) \quad \text{in} \quad \Omega.
\]

Proof. Let us put $y = y^* + w$. We will look for a control $u \in L^\infty(\Omega \times (0, T))$ such that the solution of
\[
\begin{aligned}
\partial_t w - \Delta w + F(x, t; w, \nabla w) &= u_1 \mathcal{O} \quad \text{in} \quad Q, \\
\mathcal{L} w &= 0 \quad \text{on} \quad \Sigma, \\
w(0) &= y_0 - y_0^* \quad \text{in} \quad \Omega
\end{aligned}
\]
satisfies
\[
w(x, T) = 0 \quad \text{in} \quad \Omega.
\]

Here, $F$ is given by
\[
F(x, t; s, p) = f(y^*(x, t) + s, \nabla y^*(x, t) + p) - f(y^*(x, t), \nabla y^*(x, t)),
\]
for all $(x, t) \in Q$ and $(s, p) \in \mathbb{R} \times \mathbb{R}^N$. The proof of this Lemma will be achieved if we check that such a control $u$ exists.
Notice that
\[ F(x, t; s, p) = \tilde{g}(x, t; s, p)s + \tilde{G}(x, t; s, p) \cdot p, \]
where
\[ \tilde{g}(x, t; s, p) = \int_0^1 \frac{\partial f}{\partial y^*}(y^*(x, t; s, \lambda p) + \lambda s, \nabla y^*(x, t; s, \lambda p) + \lambda p) \, d\lambda \]
and
\[ \tilde{G}_i(x, t; s, p) = \int_0^1 \frac{\partial f}{\partial y^*}(y^*(x, t; s, \lambda p) + \lambda s, \nabla y^*(x, t; s, \lambda p) + \lambda p) \, d\lambda \quad \text{for } 1 \leq i \leq N. \]

Thus, in view of (9) and the fact that \( y^* \in C^0([0, T]; W^{1, \infty}(\Omega)) \), it is clear that \( F \) satisfies the assumptions of Remark 3.2. This is sufficient to ensure that \( u \) exists. This completes the proof of this Lemma. \[ \square \]

Now, we argue as follows:
- There exists \( \delta_0 > 0 \), only depending on \( \Omega, y_d \) and \( f \), such that, for each \( \delta \in (0, \delta_0) \), the system

\[ \begin{align*}
\frac{\partial w}{\partial t} - \Delta w + f(w, \nabla w) &= 0 & \text{in } \Omega \times (T - \delta, T), \\
0 &= w & \text{on } \partial \Omega \times (T - \delta, T), \\
w(x, T - \delta) &= y_d(x) & \text{in } \Omega,
\end{align*} \tag{66} \]

has exactly one solution \( w \in C^0([T - \delta, T]; W^{1, \infty}(\Omega)) \) also satisfying

\[ \|w(\cdot, T) - y_d\|_{L^2} \leq \epsilon. \tag{67} \]

Obviously, we can associate to \( \epsilon \) a parameter \( \delta \in (0, \delta_0) \) (small enough) such that, for the corresponding solution \( w \) to (66), one has:

\[ \|w(\cdot, T) - y_d\|_{L^2} \leq \epsilon. \tag{68} \]

We fix \( \delta \) and \( w \) verifying (66), (67) and (68).
- There exists \( v_1 \in L^\infty(\Omega \times (0, T - \delta)) \) such that the corresponding system

\[ \begin{align*}
\frac{\partial y_1}{\partial t} - \Delta y_1 + f(y_1, \nabla y_1) &= v_1 \mathbf{1}_\Omega & \text{in } \Omega \times (0, T - \delta), \\
y_1 &= 0 & \text{on } \partial \Omega \times (0, T - \delta), \\
y_1(x, 0) &= y_0(x) & \text{in } \Omega
\end{align*} \tag{69} \]

possesses exactly one solution \( y_1 \in C^0([0, T - \delta]; W^{1, \infty}(\Omega)) \), with

\[ y_1(x, T - \delta) = y^*(x, T - \delta) \quad \text{in } \Omega. \]

This is a consequence of Lemma 4.1.
- From (68), we see that, in \([T - \delta, T]\), our task is reduced to drive the system exactly from the state \( y^*(\cdot, T - \delta) \) to the state \( w(\cdot, T) \). But we can use again Lemma 4.1 and deduce the existence of a control \( u_2 \in L^\infty(\Omega \times (T - \delta, T)) \) such that the corresponding system

\[ \begin{align*}
\frac{\partial u_2}{\partial t} - \Delta u_2 + f(u_2, \nabla u_2) &= v_2 \mathbf{1}_\Omega & \text{in } \Omega \times (T - \delta, T), \\
u_2 &= 0 & \text{on } \partial \Omega \times (T - \delta, T), \\
u_2(x, T - \delta) &= y^*(x, T - \delta) & \text{in } \Omega
\end{align*} \tag{70} \]
possesses one solution \( y_2 \in C^0([T - \delta, T]; W^{1,\infty}(\Omega)) \) satisfying
\[ y_2(x, T) = w(x, T) \quad \text{in } \Omega. \]

Let us now set
\[ v = \begin{cases} v_1 & \text{in } [0, T - \delta], \\ v_2 & \text{in } [T - \delta, T]. \end{cases} \]
The associate state is
\[ y = \begin{cases} y_1 & \text{in } [0, T - \delta], \\ y_2 & \text{in } [T - \delta, T]. \end{cases} \]

Therefore, we have found a control \( v \in L^\infty(\mathcal{O} \times (0, T)) \) such that the corresponding system (1) possesses a solution \( y \) satisfying (4). This completes the proof of Theorem 1.2.

5. Sketch of the proofs of the boundary controllability results. We devote this Section to sketch briefly the proofs of Theorems 1.3 and 1.4. Both results are implied by the results established in the case of internal controllability.

For instance, let us refer to the proof of Theorem 1.3. Let us assume, for simplicity, that \( \tilde{y}_0 \in W^{2,p}(\Omega) \cap V \) for some \( p > N \). Recall that \( f: \mathbb{R} \times \mathbb{R}^N \rightarrow \mathbb{R} \) is a locally Lipschitz-continuous function and satisfies \( f(0, 0) = 0 \) and (6). Let \( G \) be a bounded open set with boundary \( \partial G \) of class \( C^2 \) such that \( \Omega \subset G \) and \( \partial \Omega \cap G = \gamma \). Let \( \mathcal{O} \) be an open subset of \( G \setminus \overline{\Omega} \). There exists a function \( \tilde{y}_0 \in W^{2,p}(G) \cap H^1_0(G) \) such that \( \tilde{y}_0 = y_0 \) in \( \Omega \) and
\[ \| \tilde{y}_0 \|_{W^{2,p}(G)} \leq C \| y_0 \|_{W^{2,p}(\Omega)}. \]
where \( C \) is a positive constant only depending on \( \Omega \) and \( G \).

Let \( \tilde{v} \in L^\infty(\mathcal{O} \times (0, T)) \) be a control, furnished by Theorem 1.1, such that
\[
\begin{aligned}
&\left\{ \begin{array}{ll}
\partial_t \tilde{y} - \Delta \tilde{y} + f(\tilde{y}, \nabla \tilde{y}) = \tilde{v} l_0 & \text{in } G \times (0, T), \\
\tilde{y} = 0 & \text{on } \partial G \times (0, T), \\
\tilde{y}(x, 0) = \tilde{y}_0(x) & \text{in } G,
\end{array} \right.
\end{aligned}
\]
possesses exactly one solution \( \tilde{y} \in C^0([0, T]; W^{1,\infty}(G)) \) with
\[ \tilde{y}(x, T) = 0 \quad \text{in } G. \]

Let \( v \) be the trace of \( \tilde{y} \) on \( \gamma \times (0, T) \). Then \( v \in L^\infty(\gamma \times (0, T)) \) and the restriction to \( \Omega \times (0, T) \) of \( \tilde{y} \) solves the corresponding system (2). This proves Theorem 1.3.

In order to prove Theorem 1.4, it suffices to argue in a similar way.

REFERENCES


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