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A Note on the Minimum Effort Control Problem*

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1. INTRODUCTION

By a *continuous linear system* we shall mean a system with input u and output x, governed for $t \geqslant t_0$ by the system of integral equations

$$x(t) = \Phi(t, t_0)\, x^0 + \Phi(t, t_0) \int_{t_0}^{t} \Phi(t_0, s)\, B(s)\, u(s)\, ds. \qquad (1)$$

Here $u(t)$ and $x(t)$ are (real or complex) vector functions with m and n components respectively and $\Phi(t, s)$ denotes the system transition matrix. In [1] Neustadt studied various "effort" functions $\epsilon(u)$ associated with such a system. In particular he showed that if the time T is fixed and effort is defined by

$$\epsilon(u) = \left(\int_0^T \sum_{j=1}^{m} | u_j(t) |^p \, dt\right)^{1/p} \qquad 1 < p < \infty$$

then to each target state $x(T)$ there corresponds a unique minimum effort control $u^*(t)$ which transfers x from x^0 to $x(T)$ in time T. The precise value $\epsilon(u^*)$ of the minimum effort was computed as well as the explicit form of the control vector $u^*(t)$.

In this note we will formulate and solve a generalization of Neustadt's problem. The result yields the existence and uniqueness of a minimum effort control and its precise form for a wide class of effort functions and includes the cases of discrete and composite (discrete-continuous) linear systems.

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2. The Minimum Effort Problem

To motivate what follows, let us consider the system of Eq. (1). For convenience we suppose the system is initially at rest so that $x^0 = 0$. Let B denote the cartesian product

$$L_p(\tau) \times L_p(\tau) \times \cdots \times L_p(\tau), \qquad \tau = [t_0, T], \qquad 1 < p < \infty$$

where $L_p(\tau)$ consists, as usual, of those complex valued Lebesgue measurable functions on τ whose pth power is integrable. Then to each $u \in B$ there corresponds a unique x satisfying Equation (1). In particular, at time T we have

$$x(T) = \Phi(T, t_0) \int_{t_0}^{T} \Phi(t_0, s)\, B(s)\, u(s)\, ds.$$

With K denoting either the real or complex numbers, this leads us to define a transformation S from B to K^n by writing $Su = x(T)$. It is easy to verify that S is linear. Moreover, with any choice of product norms on B and K^n, S is bounded. Since it is clear that

$$\| u \| = \left(\int_{t_0}^{T} \sum_{i=1}^{m} | u_i(t) |^p \, dt \right)^{1/p} \qquad 1 < p < \infty$$

defines a norm on B, we see that a natural generalization of the control problem of Neustadt is the following.

Problem. Let B and R be Banach spaces and T a bounded linear transformation from B into R. For each ξ in the range of T find an element $u \in B$ satisfying $Tu = \xi$ which minimizes $\| u \|$.

Consider the set $T^{-1}(\xi)$ of all pre-images of ξ under T. The solution to the general minimum effort problem must then answer the following questions: Does $T^{-1}(\xi)$ contain an element of minimum norm? If so, is this element unique? Finally, if both these answers are yes, and if we write $T^{\dagger}\xi$ for the unique minimum pre-image of ξ under T, what is the nature of the function $T^{\dagger}$ so defined, and more specifically, how can one compute its values?

Initially, we allow B to be an arbitrary (real or complex) Banach space. After having answered the first two questions we will see the need of requiring two additional properties of B (namely reflexivity and rotundity) to insure the existence of the minimum energy function $T^{\dagger}$ associated with T. For convenience in studying $T^{\dagger}$ we will then impose a third restriction on B (smoothness). As regards T, we require that it be *onto* R. This amounts to assuming that T has a closed range and hence in particular, if T has a finite dimensional range, results in no loss of generality.

We begin with two examples which show that some additional restriction on B is needed.

EXAMPLE 1. Let C denote the set of all real (or complex) valued continuous functions or the interval $0 \leqslant t \leqslant 1$ which vanish at $t = 0$. Then C is a closed subspace of the usual Banach space of continuous functions on $[0, 1]$, and hence is a Banach space. Let T be the bounded linear transformation from C to K defined by

$$Tu = \int_0^1 u(t)\, dt.$$

Then it is easy to see that

(1) $\inf\{\| u \| : Tu = 1\} = 1$.

(2) $| Tu | < 1$ if $u \in C$ has norm 1.

It follows that the vector (number) 1 does not have a minimum pre-image under T.

EXAMPLE 2. Let D denote the plane equipped with the norm

$$\| x \| = | x_1 | + | x_2 | \qquad \text{if} \qquad x = (x_1, x_2).$$

On D we define the linear transformation T by

$$Tx = x_1 + x_2 .$$

It is obvious that $\| T \| = 1$ and hence that any $x \in D$ satisfying $Tx = 1$ has norm $\geqslant 1$. It follows that *both* of the vectors $(0, 1)$ and $(1, 0)$ are minimum pre-images of 1 under T.

In short, the minimum effort function $T^\dagger$ associated with T can fail to exist by virtue of either a lack of or an overabundance of minimum pre-images. It is worth observing that the space C above is not reflexive and the space D has a "flat" unit ball (connect the points $(0, 1)$, $(1, 0)$, $(-1, 0)$, $(0, -1)$). We now proceed to remedy both these defects in B.

DEFINITION. Let $U = \{x : \| x \| \leqslant 1]$ be the unit ball in B and ∂U the boundary of U. B is called *rotund* [2] or *strictly convex* [3] if one of the following equivalent conditions satisfied:

(1) ∂U contains no line segments.

(2) $\| x_1 + x_2 \| = \| x_1 \| + \| x_2 \|$ implies $x_2 = \lambda x_1$ or $x_1 = \lambda x_2$ for some $\lambda \geqslant 0$.[1]

[1] Observe that it follows from (2) that rotundity is preserved by any linear isometry.

(3) For each bounded linear functional φ on B there is at most one $x \in U$ with $\langle x, \varphi \rangle = \varphi(x) = \| \varphi \|$.

(4) Each convex subset C of B has at most one minimum element (i.e., there is at most one vector $x \in C$ satisfying $\| x \| \leqslant \| z \|$ for all $z \in C$.

The following lemma lists some examples of rotund Banach spaces.

LEMMA 1. (1) *Any Hilbert space is rotund.*

(2) *The spaces l_p, L_p are rotund for $1 < p < \infty$.*

(3) *If $B_1, \cdots, B_n$ are rotund Banach spaces, then so is*

$$B = B_1 \times B_2 \times \cdots \times B_n$$

when the norm of $x = (x_1, x_2, \cdots, x_n)$ in B is defined by either of

$$\| x \| = \Big(\sum_i \| x_i \|^p \Big)^{1/p} \qquad 1 < p < \infty$$

$$\| x \| = \Big(\sum_{i,j} a_{ij} \| x_i \| \, \| x_j \| \Big)^{1/2}$$

where $[a_{ij}]$ is a strictly positive $n \times n$ matrix each of whose entries is nonnegative.

PROOF. The first assertion follows immediately from (2) of the above definition and the parallelogram law. The second is well-known and may be found in [4; p. 211] for example. The proof of (3) is straightforward but somewhat detailed and hence will be omitted.

Observe now that because T is linear and continuous the set $T^{-1}(\xi)$ is convex and closed for each $\xi \in R$. The following theorem therefore gives necessary and sufficient conditions on B for our first two questions to be answered affirmatively for *every* T on B.

THEOREM 1. *Let B be a Banach space. Then each closed convex set C in B has at least one (at most one) minimum element if and only if B is reflexive (rotund).*

PROOF. Property (4) above establishes half of the theorem. Suppose then that B is reflexive. Then U is weakly compact and consequently, if

$$\alpha = \inf \{ \| z \| : z \in C \},$$

the sets

$$C_n = \{ z \in C : \| z \| \leqslant \alpha + 1/n \} \qquad (n = 1, 2, \cdots)$$

form a decreasing sequence of non-empty, weakly compact subsets of B and therefore have nonempty intersection. The fact that reflexivity of B is also necessary was recently shown by Phelps [5].

Henceforth we assume that B is reflexive and rotund and focus attention on the function $T^{\dagger}$.

3. The Minimum Effort Function

We begin by examining a special case.

THEOREM 2. *If $B = H$ is a Hilbert space, N is the null space of T and $M = N^{\perp}$, then $T^{\dagger} = T_M^{-1}$ is the inverse of the restriction of T to M.*

PROOF. The transformation T_M is $1 - 1$, continuous, and onto the Banach space R and hence, by the Closed Graph Theorem, is invertible. Let ξ be a fixed vector in R and write $u_\xi = T_M^{-1}(\xi)$. If $u \in H$ is any pre-image of ξ, then

$$u = (u - u_\xi) + u_\xi$$

is the unique decomposition of u in $N \oplus M$ and hence

$$\| u \|^2 = \| u - u_\xi \|^2 + \| u_\xi \|^2 \geqslant \| u_\xi \|^2$$

The result follows from the definition of $T^{\dagger}$.

It is clear that the proof and even the statement of Theorem 2 makes no sense in B. As a matter of fact, it turns out that the function $T^{\dagger}$ will not in general be linear, and different techniques are necessary.

If E is a Banach space then the Hahn-Banach theorem shows that to each non-zero x in E there corresponds at least one $\varphi \in E^*$ such that

$$\| \varphi \| = 1, \qquad \langle x, \varphi \rangle = \| x \|$$

If E is reflexive this result applied to E^* shows that to each $\varphi \neq 0$ in E^* there corresponds at least one $x \in E$ such that

$$\| x \| = 1, \qquad \langle x, \varphi \rangle = \| \varphi \|$$

To insure that for each $\varphi \neq 0$ in E^* the corresponding element x in E is unique it is sufficient (and in fact, necessary) that E be rotund. Thus if E is a rotund reflexive Banach space and φ is a continuous linear functional on E, then φ is not only bounded on the unit ball of E, but in fact attains its supremum, and does so uniquely.

The preceeding remarks show that with a rotund reflexive Banach space B

we are justified in writing $\bar{\varphi}$ for the unique vector in B of norm 1 satisfying $\langle \bar{\varphi}, \varphi \rangle = \| \varphi \|$ and in referring to $\bar{\varphi}$ as the *extremal* of φ. We adopt the convention that the extremal 0 of the 0 functional is the 0 vector in B.

Now let $x \neq 0$ be a vector in B. Regarding x as a linear functional on B the Hahn-Banach produced φ shows that x attains its supremum on the unit ball of B, and that rotundity of B^* is necessary and sufficient for x to attain its supremum uniquely. Thus, requiring that both B and B^* be rotund (and reflexive) we can denote this unique φ by $\bar{x}$ and speak of the *extremal* of x. Since the conjugate of any of the spaces of Lemma 1 is another of the same type it is clear that each of these is still a possible candidate for B.

A Banach space E is called *smooth* if at each point of ∂U there is exactly one supporting hyperplane of U. Day [2; p. 112] notes that the following properties are equivalent:

(1) E is smooth.

(2) For each $x \in \partial U$ there is at most one $\varphi \in E$ such that $\| \varphi \| = 1$ and $\varphi(x) = 1$.

(3) The functional $x \to \| x \|$ has a Gateaux differential at each point of ∂U; that is,

$$\lim_{\epsilon \to 0} \frac{\| x + \epsilon h \| - \| x \|}{\epsilon}$$

exists for each $x \in \partial U$ and $h \in E$.[2]

In addition, it is not difficult to see that for any Banach space E, E is smooth (rotund) if E^* is rotund (smooth). It follows from this that if E is reflexive, E^* is rotund if and only if E is smooth. Accordingly, to enable the dual use of the term extremal in B, we henceforth require that B be rotund, reflexive, and smooth. (This latter hypothesis will be seen to be dispensible.) We note the following properties of the extremal operation:

(i) $\bar{\bar{x}} = x/\| x \|$ for $x \neq 0$ in B,

(ii) $\bar{\bar{\varphi}} = \varphi/\| \varphi \|$ for $\varphi \neq 0$ in B,

(iii) $\overline{\lambda x} = (| \lambda |/\lambda)\, \bar{x}$ any complex scalar λ.

The proof of the following theorem is straightforward.

THEOREM 2. *Let x be given in B. The Gateaux derivative of the norm at x*

$$G(x, h) = \lim_{\epsilon \to 0} \frac{\| x + \epsilon h \| - \| x \|}{\epsilon}$$

[2] This shows that any isometric copy of a smooth space is smooth.

exists for each $h \in B$ and the mapping $h \to G(x, h)$ defines a real linear functional on B of norm 1 which assumes the value $\| x \|$ at x. Consequently, if B is a real *linear space this is the extremal $\bar{x}$ of x. In general this is the real part of the extremal of x:*

$$G(x, h) = \mathrm{Re}\, \langle h, \bar{x} \rangle \qquad (\text{all } h \in B).$$

Recall that the conjugate T^* of T is the bounded linear transformation from R^* to B^* defined for $\varphi \in R^*$ by

$$\langle u, T^*\varphi \rangle = \langle Tu, \varphi \rangle \qquad u \in B.$$

That is, $T^*\varphi$ is the linear functional on B whose value at u is the number $\langle Tu, \varphi \rangle$. The Hahn-Banach theorem shows that $\| T^* \| = \| T \|$. The fact that T is onto R shows that T^* is one-to-one.

The next result deals with another special case.

LEMMA 2. *Suppose that for some $\xi \in R$ we have $\| T^\dagger \xi \| = \| \xi \|$. Then $T^\dagger \xi$ is given by the formula.*

$$T^\dagger \xi = \| \xi \| \, \overline{T^* \bar{\xi}}.$$

Here, if the norm on R is not smooth, $\bar{\xi}$ is understood to be any extremal of ξ.

PROOF. Without loss of generality we may assume that $\| T \| = 1$. Then $\| T^* \| = 1$ hence $\| T^*(\bar{\xi}) \| \leqslant 1$. This, together with

$$\langle T^\dagger(\xi), T^*(\bar{\xi}) \rangle = \langle \xi, \bar{\xi} \rangle = \| \xi \| = \| T^\dagger(\xi) \|$$

shows that

$$T^*(\bar{\xi}) = \overline{T^\dagger(\xi)}.$$

Taking extremals we obtain the desired formula.

REMARK. The formula in the preceeding lemma yields $T^\dagger(\xi)$ to within a positive constant in terms of the extremal operations on R and B. It is generally an easy task to write an explicit formula for construction of extremals. For example, consider the product $B = B_1 \times B_2 \times \cdots B_n$ where the B_i are rotund and B is normed as in Lemma 1. Each bounded linear functional φ on B may be identified with an n-tuple $(\varphi_1, \varphi_2, \cdots, \varphi_n)$ where $\varphi_i \in B_i^*$. Let $\bar{\varphi}_i$ be the extremal of φ_i in B_i. Then it is easy to verify that with the p-norm on B the extremal $\bar{\varphi}$ of φ is given by

$$\bar{\varphi} = (\alpha_1 \bar{\varphi}_1, \alpha_2 \bar{\varphi}_2, \cdots, \alpha_n \bar{\varphi}_n)$$

$$\alpha_i = \alpha^{-1} \| \varphi_i \|^{q-1}, \qquad \alpha = \left(\sum \| \varphi_i \|^q \right)^{1/q}, \qquad q = \frac{p}{p-1}.$$

Similarly, with the matrix norm on B, φ has the form

$$\bar{\varphi} = (\beta_1\bar{\varphi}_1, \beta_2\bar{\varphi}_2, \cdots, \beta_n\bar{\varphi}_n)$$

$$\beta_i = \beta^{-1} \sum_j b_{ij} \| \varphi_j \|, \qquad \beta = \sum_{i,j} b_{ij} \| \varphi_i \| \| \varphi_j \|$$

where $[b_{ij}]$ is the inverse of the matrix $[a_{ij}]$.

These formulas imply that the conjugate space B^* is (isometrically isomorphic to) the product $B_1^* \times B_2^* \times \cdots \times B_n^*$ with the respective norms of $\varphi = (\varphi_1, \varphi_2, \cdots, \varphi_n)$ given by

$$\| \varphi \| = \left(\sum_i \| \varphi_i \|^q\right)^{1/q}, \qquad \| \varphi \| = \sum_{i,j} b_{ij} \| \varphi_i \| \| \varphi_j \| .$$

It follows that if each B_i is also reflexive and smooth, so that each $x = (x_1, x_2, \cdots x_n)$ in B has an extremal $\bar{x}$ in B^*, then

$$\bar{x} = (\beta_1\bar{x}_1, \beta_2\bar{x}_2, \cdots, \beta_n\bar{x}_n)$$

$$\beta_i = (\beta^{-1} \| x_i \|)^{p-1} \qquad \beta = \left(\sum_i \| x_i \|^p\right)^{1/p}$$

and

$$\bar{x} = (\delta_1\bar{x}_1, \delta_2\bar{x}_2, \cdots, \delta_n\bar{x}_n)$$

$$\delta_i = \delta^{-1} \sum_j a_{ij} \| x_j \|, \qquad \delta = \sum_{i,j} a_{ij} \| x_i \| \| x_j \| .$$

In particular, if $B = l_{p,n}$ is the space of complex n-tuple $\xi = (\xi_1, \xi_2, \cdots, \xi_n)$ with the norm

$$\| \xi \| = \left(\sum_i \| \xi_i \|^p\right)^{1/p}$$

then

$$\bar{\xi} = (\eta_1, \eta_2, \cdots, \eta_n)$$

where

$$\eta_i = \begin{cases} \dfrac{\bar{\xi}_i}{| \xi_i |}\left(\dfrac{| \xi_i |}{\| \xi \|}\right)^{p-1} & \text{if} \quad \xi_i \neq 0 \\ 0 & \text{if} \quad \xi_i = 0. \end{cases}$$

A precisely analogous formula holds in L_p $(1 < p < \infty)$.

Observe also that if T arises from a linear system in the sense that for a system input u, Tu is the value of the output state vector at some fixed instant, then its range is finite dimensional so that T^*, being a linear transformation on a finite dimensional space, will be given by a matrix. Thus, evaluation of $T^{\dagger}(\xi)$ is reduces to familiar computations. Finally, note that the preceeding remarks in particular determine the extremal operations in (suitably normed) input spaces of the form

$$B = l_{p_1,n_1} \times l_{p_2,n_2} \times \cdots \times l_{p_k,n_k} \times L_{q_1} \times L_{q_2} \times \cdots \times L_{q_l}$$

where $1 \leqslant n_i \leqslant \infty$ and $1 < p_i, q_i < \infty$. In other words, T may represent systems with digital and/or functional inputs.

LEMMA 3. *Let $C = T(U)$ be the image of the unit ball in B. Then C is a convex, circled,*[3] *weakly compact, neighborhood of* 0 *in R.*

PROOF. Since T is linear, C is convex and circled. The Opening Mapping Theorem shows that $T(U)$ contains a multiple of the unit ball in R, and hence is a neighborhood of 0. Finaly, it is known [6; p. 115] that a continuous linear mapping from one Banach space into another remains continuous when both spaces are equipped with their weak topologies. Since U is weakly compact in B it follows that $T(U)$ is weakly compact in R.

It follows from Lemma 3 that C is *radial* at 0. That is, for each $\xi \in R$ there is a scalar $\lambda > 0$ such that $\xi \in \lambda C$. Hence [7] the Minkowski functional p given by

$$p(\xi) = \inf\{\lambda > 0 : \xi \in \lambda C\}$$

is defined and finite on all of R. Since C is convex and circled the functional p is subadditive and absolutely homogeneous.

$$p(\xi + \zeta) \leqslant p(\xi) + p(\zeta) \qquad \xi, \zeta \in R$$
$$p(\lambda\xi) = |\lambda| p(\zeta).$$

The next lemma lists a few facts we will need.

LEMMA 4. (i) *The interior of C consists of those $\xi \in R$ for which $p(\xi) < 1$.*

(ii) *$\partial C = \{\xi \in R : p(\xi) = 1\}$ is the boundary of C.*

(iii) *$\partial C \subset T(\partial U)$.*

PROOF. The assertions (i) and (ii) are well known and follow directly from the definition of p. As for (iii), if $\xi \in \partial C$, then $\xi \in C$ and hence $\xi = Tu$ for some $u \in U$. Since by (ii), $p(\xi) = 1$, we have $\lambda^{-1}\xi \notin C$ for all $\lambda < 1$. But then $\lambda^{-1}u \notin U$ for all $\lambda < 1$. This means that $\| u \| \geqslant 1$, and since $u \in U$, that $\| u \| = 1$.

[3] A set C in a vector space E is *circled* if $\lambda C \subset C$ for all $|\lambda| \leqslant 1$.

REMARK. It is easy to construct examples to show that the reverse inclusion (iii) is not valid in general.

COROLLARY. *The functional p is a norm on R equivalent to the given norm. In fact for some constant $k > 0$ we have*

$$\frac{1}{\| T \|} \| \xi \| \leqslant p(\xi) \leqslant k \| \xi \| \qquad (\xi \in R).$$

PROOF. Suppose $\| \xi \| > 0$ and let λ be any positive scalar with $\xi \in \lambda C$. Then $1/\lambda\, \xi \in T(U)$ and hence

$$\left\| \frac{1}{\lambda} \xi \right\| \leqslant \| T \| .$$

This implies that

$$p(\xi) \geqslant \frac{\| \xi \|}{\| T \|}$$

and hence that p is a norm on R.

By Lemma 3, $C = \{\xi : p(\xi) \leqslant 1\}$ is a neighborhood of 0 in R and hence there is an $\epsilon > 0$ such that $p(\zeta) \leqslant 1$ if $\| \zeta \| \leqslant \epsilon$. Hence $p(\xi) \leqslant (1/\epsilon) \| \xi \|$ for all $\xi \in R$.

We are now able to obtain the promised characterization of $T^{\dagger}(\xi)$. If N is a *real* linear functional on a real vector space E we will say that a subset C of E *lies to the left* of the hyperplane $H = \{\xi \in E : \langle \xi, N \rangle = \alpha_0\}$ provided that $\langle \xi, N \rangle \leqslant \alpha_0$ for all $\xi \in C$. *H supports C* if it meets C and if C lies entirely on one side of H. A geometric form of the Hahn-Banach Theorem, valid in any topological vector space, asserts that a closed convex set with nonempty interior has a supporting hyperplane through each of its boundary points [8; p. 72].

THEOREM 4. *Let $\xi_0 \neq 0$ be a given vector in R and let $\alpha = p(\xi_0)^{-1}$. Then there exists a unique vector N in the unit sphere of R^* such that*

$$T^{\dagger}(\xi_0) = p(\xi_0)\, \overline{T^* N}.$$

The functional N is uniquely determined by the conditions

(i) $\| N \| = 1$.

(ii) *C lies to the left of the hyperplane $H = \{\xi \in R : \langle \xi, N \rangle = \alpha \langle \xi_0 , N \rangle\}$. If B is a complex space this last requirement is to be interpreted as saying that*

$$\operatorname{Re} \langle \xi, N \rangle \leqslant \operatorname{Re} \langle \alpha \xi_0 , N \rangle \qquad \text{all} \qquad \xi \in C.$$

PROOF. Suppose first that B is real. Since C is closed, convex, and has nonempty interior it follows that there is a supporting hyperplane of C at $\alpha\xi_0$ and hence a functional N satisfying (i) and (ii). Note that since $0 \in C$, N is nonnegative at $\alpha\xi_0$.

To prove the theorem it evidently suffices to prove:

(a) $\varphi \in R^*$ satisfies $T^\dagger(\xi_0) = p(\xi_0)\,\overline{T^*\varphi}$ if and only if (ii) holds for φ.

(b) There is at most one φ of norm 1 satisfying $T^\dagger(\xi_0) = p(\xi_0)\,\overline{T^*\varphi}$.

The proof of (b) follows from the fact that the mapping $\varphi \to \overline{T^*\varphi}$ is one-to-one from the unit sphere of R^* into the unit sphere of B.

Suppose next that $T^\dagger(\xi_0) = p(\xi_0)\,\overline{T^*\varphi}$ for some $\varphi \in R^*$. Then

$$\xi_0 = T^\dagger(\xi_0) = \alpha^{-1}T(\overline{T^*\varphi})$$

and hence

$$\begin{aligned}\langle \xi_0, \varphi\rangle &= \langle T(\overline{T^*\varphi}), \varphi\rangle = \langle \overline{T^*\varphi}, T^*\varphi\rangle \\ &= \| T^*\varphi \| \geqslant \langle u, T^*\varphi\rangle = \langle Tu, \varphi\rangle\end{aligned}$$

for all $u \in U$ and since $C = T(U)$ this shows that φ satisfies (ii). (Note that since φ is a real functional, the number $\langle u, T^*\varphi\rangle$ is real for any $u \in U$.)

Finally, suppose $\varphi \in R^*$ satisfies (ii). Since $\alpha\xi_0 \in \partial C$ there is a $u_0 \in \partial U$ with $Tu_0 = \alpha\xi_0$. Then

$$\langle u_0, T^*\varphi\rangle = \langle \alpha\xi_0, \varphi\rangle = | \langle \alpha\xi_0, \varphi\rangle | = | \langle u_0 T^*\varphi\rangle |.$$

Hence by definition of the norm of the functional $T^*\varphi$ on B we have

$$\| T^*\varphi \| = \sup_{u \in U} | \langle u, T^*\varphi\rangle | \geqslant \langle u_0, T^*\varphi\rangle$$

and since $\overline{T^*\varphi} \in U$,

$$\langle \xi_0, \varphi\rangle \geqslant \langle T(\overline{T^*\varphi}), \varphi\rangle = \| T^*\varphi \|.$$

We conclude that $\langle u_0, T^*\varphi\rangle = \| T^*\varphi \|$ and hence that $u_0 = \overline{T^*\varphi}$. Thus the vector $\alpha^{-1}\overline{T^*\varphi}$ is a pre-image (under T) of ξ_0 and to prove that this is $T^\dagger(\xi_0)$ it remains only to show that any $u \in B$ satisfying $Tu = \xi_0$ has a norm of at least α^{-1}. This however follows from

$$\langle u, T^*\varphi\rangle = \langle \xi_0, \varphi\rangle = \alpha^{-1}\langle \alpha\xi_0, \varphi\rangle = \alpha^{-1} \| T^*\varphi \|$$

and the fact that

$$\| u \| = \sup_{f \in B^*} \frac{| \langle u, f\rangle |}{\| f \|}.$$

Suppose now that B is a complex space. Then [7; p. 118] the boundary point $\alpha\xi_0$ of C can be separated from C by a complex linear functional N in the sense that

$$\operatorname{Re}\langle\xi, N\rangle \leqslant \operatorname{Re}\alpha\langle\xi_0, N\rangle \qquad \text{all} \qquad \xi \in C.$$

The remainder of the argument now proceeds as before.

REMARK. The unique vector N in R^* satisfying (i) and (ii) deserves, in a natural way, to be called the *outward normal* to C at $\alpha\xi_0$. We have shown that there is an outward normal to C at each of its boundary points.

Observe also that it follows from the theorem that $\| T^\dagger(\xi) \| = p(\xi)$. Since the latter function is a (uniformly) continuous function, we see that the minimum effort associated with each state $\xi \in R$ is a continuous function of ξ: if two vectors ξ_1, ξ_2 in R are close, and if u_1 and u_2 are their minimum pre-images under T, then the norms of u_1 and u_2 are correspondingly close.

It is easy to show that in case $B = H$ is a Hilbert space, the formulas $T^\dagger(\xi) = T_M^{-1}\,\xi$ and $T^\dagger(\xi) = p(\xi)\,\overline{T^*N}$ are consistent.

LEMMA 5. *For each $\xi \in R$, set $|\,\xi\,| = p(\xi)$. Then $|\ |$ is a norm on R, equivalent to the given norm. Let R_1 denote the space R equipped with the norm $|\ |$. Then R_1 is rotund and smooth.*

The proof of Lemma 5 is left to the reader. Now it follows from Lemma 5 and Theorem 4 that the definition $|\,\xi\,| = p(\xi)$ yields a norm on R for which

$$|\,\xi\,| = \| T^\dagger(\xi) \|$$

holds identically in ξ. It therefore follows from Lemma 2 that

$$T^\dagger(\xi) = p(\xi)\,\overline{T^*(\xi')} \qquad \xi \in R$$

where ξ' denotes the extremal of ξ relative to the norm $|\ |$. That is, ξ' is characterized by the equations

$$\sup_{p(\zeta)=1} |\langle\zeta, \xi\rangle| = 1, \qquad \langle\xi, \xi'\rangle = p(\xi).$$

Since by Lemma 1(c) applied to R^*,

$$\overline{T^*(\xi'/\|\,\xi'\,\|)} = \overline{T^*(\xi')}$$

we have proven part of the following:

THEOREM 5. *Let ξ be a fixed boundary point of C and let N be the outward normal to C at ξ. Then*

(i) $N = \xi'/\|\,\xi'\,\|$ *where ξ' is the extremal of ξ relative to the norm $p(\xi)$ on R.*

(ii) *N is the unique vector φ in R^* of norm* 1 *satisfying* $\| T^*\varphi \| = \langle \xi, \varphi \rangle$.

(iii) $N = \xi'/\| \xi' \|$ *where ξ' is the bounded linear functional on R whose real part is defined for $\zeta \in R$ by*

$$\mathrm{Re}\,\langle \zeta, \xi' \rangle = \lim_{\epsilon \to 0} \frac{| \xi + \epsilon\zeta | - | \xi |}{\epsilon} = \lim_{\epsilon \to 0} \frac{p(\xi + \epsilon\zeta) - p(\xi)}{\epsilon}.$$

PROOF. If $\varphi \in R^*$ satisfies $\| T^*\varphi \| = \langle \xi, \phi \rangle$, then for any $\zeta \in C$, we may *choose* $u \in U$ so that $Tu = \zeta$ to obtain

$$\langle \zeta, \varphi \rangle = \langle Tu, \varphi \rangle = \langle u, T^*\varphi \rangle \leqslant \| T^*\varphi \| = \langle \xi, \varphi \rangle$$

and hence, by Theorem 4, φ is a positive multiple of N. This proves (ii).

Now consider (iii). We observe that since R is smooth its norm has a Gateaux derivative at each point on the boundary of its unit ball. That is,

$$G(\xi, \zeta) = \lim_{\epsilon \to 0} \frac{| \xi + \epsilon\zeta | - | \xi |}{\epsilon}$$

exists for each $\xi \in \partial C$ and ζ in R. Assertion (iii) now follows from Theorem 2.

4. DISCUSSION

It is clear from the preceding results that once one knows the set C relatively simple computations furnish (a) the minimum effort T needs to reach any given state ξ in R and (b) the precise pre-image $T^{\dagger}(\xi)$ of ξ whose effort is this minimum value. Indeed the boundary of the set αC is a "level surface" consisting of those states $\xi \in R$ which T can obtain with a minimum energy of precisely α, and the outward normals to C determine (to within a positive multiple) the class of minimum energy inputs. However, even in the relatively simple case in which B is finite dimensional, the equation $C = T(U)$ is unsuitable for specifying C. It is therefore, natural to seek a simpler way to determine C. For example, if C is a multiple of the unit ball in R we need only one parameter to specify C completely; if C is an ellipsoid we need only to determine the size of its semiaxes, and so on. In any event the conditions of Theorem 5 are sufficient to compute N by iterative procedures if necessary.

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