WORKING PAPERS IN ECONOMICS

THE LIMITS OF SYSTEM CONTROL THEORY FOR ECONOMIC POLICY-MAKING

by

Luigi Ermini

No. 111 July - October 1988

DEPARTMENT OF ECONOMICS

The University of Sydney
Australia 2006

WORKING PAPERS
IN ECONOMICS

THE LIMITS OF SYSTEM CONTROL THEORY FOR ECONOMIC POLICY-MAKING

by

Luigi Ermini

No. 111 July - October 1988

DEPARTMENT OF ECONOMICS

The University of Sydney
Australia 2006

THE LIMITS OF SYSTEM CONTROL THEORY FOR ECONOMIC POLICY-MAKING

by

Luigi Ermini

No. 111 July - October 1988

Abstract

This paper discusses some reasons why system control theory has had only a limited impact on economic analysis, especially on government policy-making. First, in engineering targets are well formulated and known to the controller; in economics, government's targets are often unknown or misperceived by the public. Second, in engineering the distinction between manipulated and non-manipulated variables is given, and the effectiveness of each manipulated variable established. In economics, it is often unclear which manipulated variable is actually used for policy. To this purpose, Granger causality tests - which in fact relate to causality in prediction and not to causality in control - seems inadequate. The paper also discusses some possible uses of the concept of cointegration for inference about unknown targets.

National Library of Australia Card Number and ISBN 0 949269 73 5

1. Introduction

Control theory is extensively used in economic analysis. Indeed, intertemporal choice problems - the core of modern economics - are formulated as if agents solved optimal control problems. Be it a government body, a representative consumer or a firm, intertemporal economic behavior is interpreted as the choice of a time path of decisions $m(t)$ over a specified time horizon, subject to some dynamic constraints (the laws of motions) and to some feasibility conditions, and selected according to a performance criterion defined over decisions and consequences. A fairly general formulation of an optimal control problem could be:

$$\max_{m(t)} E \int_0^T G(m(t), y(t), d(t), t)\, dt \qquad (1)$$

subject to

$$y'(t) = f(y(t), m(t), d(t), t)$$
$$y(0) = y_o$$
$$m(t) \in M \text{ for some } t$$
$$y(t) \in Y \text{ for some } t,$$

where $G(.)$ is the performance criterion; $y(t)$ is the outcome of decisions (for example, a new state for the economy) and $y'(t)$ is its first time derivative; $d(t)$ is an external disturbance of known probability distribution; E is the expectation operator based on this distribution; M, Y are feasible sets for $m(t)$ and $y(t)$; T is the time horizon, possibly infinite. For the sake of generality, $m(t)$, $y(t)$ and $d(t)$ are vectors.

Models like (1) are formulated in almost all areas of modern economics. To name a few: finance, consumption/saving decisions, investment decisions, growth theory, dynamic macroeconomic theory. Within this broad framework, then, a control problem in economics is synonymous with dynamic optimization problem, and control theory is synonymous with methods to solve problems like (1).

In particular, a large number of economic models - especially of government policy-making - are formulated as *target-oriented* control problems, a subclass of control problems that has been a traditional domain of engineering. One example of these problems is the *tracking problem*, where the choice of decisions or control actions $m(t)$ is purposefully determined to force the outcome $y(t)$ to follow a specific trajectory of values $r(t)$, or to satisfy a final value $r(T)$. A second example is the *stabilization problem*, where the choice of $m(t)$ is based on the criterion of minimizing deviations of the actual values of the outcome from desired values. In both cases, the definition of a target is *essential* to the formulation of the problem.

In this paper, the attention will be focused on this specific subclass. It is well known in the engineering literature that in a stochastic environment a *feedback* solution scheme - where $m(t)$ depends in general on both the actual and the desired values of the outcome - is superior to a *feedforward* scheme - where $m(t)$ is simply defined as a mapping between time values and values of $m \in M$ (see, for example, Astrom [1970]). Thus, the class of target-oriented control problems will be identified with the feedback scheme of Fig.1: C is the controller, whose output is the control vector m, determined from knowledge of targets and disturbances, and from feedback of actual values of outcomes. S is the system under control, whose output is the outcome y (for simplicity, no distinction is made between observations and system state). Since in general many alternative control actions can be available to achieve the same target, the controller's problem is in general formulated as an optimal control problem. Given the emphasis on the concept of a system, target-oriented control problems will be referred to as *system control problems*.

Examples abound in the engineering literature of how the development of system control theory - from the early single output-single input servomechanisms of automatic control theory to the modern multi input-multi output state space theory - has led to substantial improvements in the quality and accuracy of control of industrial processes, chemical plants, electronic systems, guidance systems, and so forth. This proven ability to solve satisfactorily real-world target-oriented control problems prompted several engineers/economists to seek similar advantages for economics, particularly in the area of government policy-making. From the early studies of Simon [1952] and Phillips [1954] to the later works, among others, of Chow [1975], Aoki [1976], Currie [1978], Feichtinger [1982], applications to economics were investigated on the assumption that concepts and methodologies could be easily transferred from the

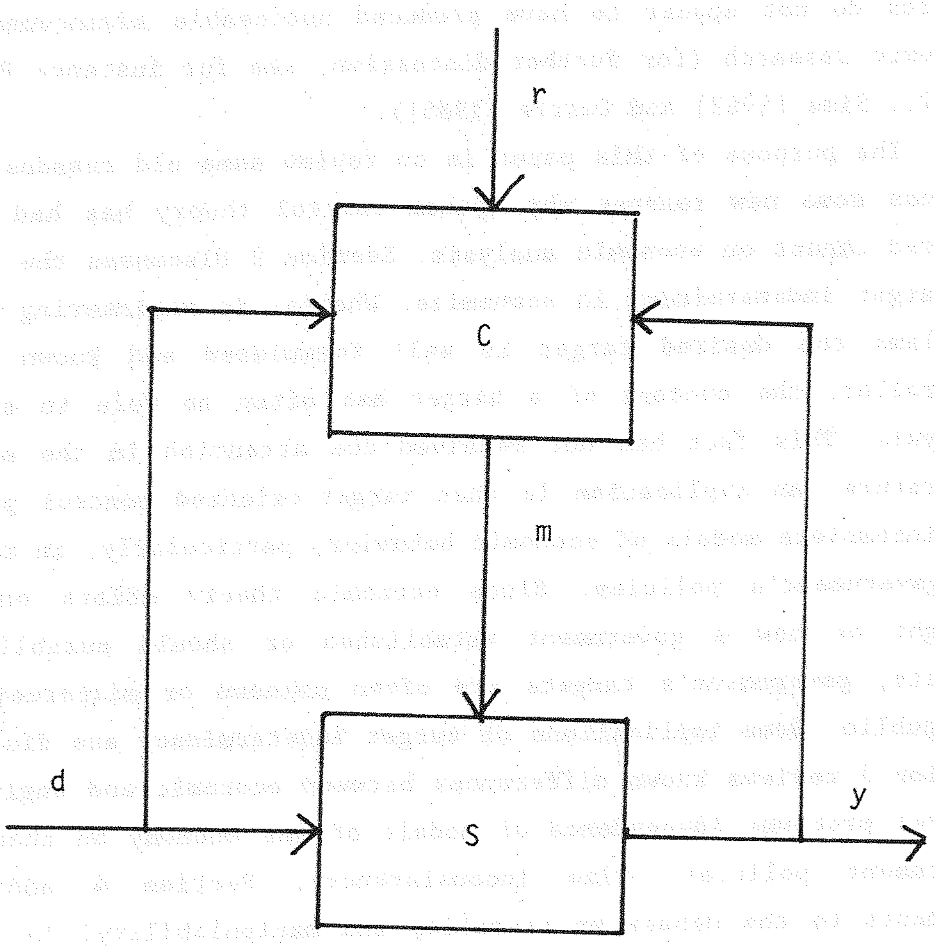

FIGURE 1 - A target-controlled system

engineering literature to problems of controlled economic growth, of stabilization policies, etc.; or even to problems of design of economic control apparatus (for example, as in Martos [1987]). However, it is a fairly common assessment among economists that these efforts do not appear to have produced noticeable advancements for economic research (for further discussion, see for instance Prescott [1977], Sims [1982] and Currie [1985]).

The purpose of this paper is to review some old reasons and to discuss some new reasons why system control theory has had only a limited impact on economic analysis. Section 2 discusses the problem of target indeterminacy in economics. Whereas in engineering control problems the desired target is well formulated and known to the controller, the concept of a target has often no role in economic analysis. This fact has not received due attention in the economic literature. An implication is that target-oriented control problems are incomplete models of economic behavior, particularly, in relation to government's policies. Since economic theory offers only few insight on how a government establishes or should establish its targets, government's targets are often unknown or misperceived by the public. Some implications of target indeterminacy are discussed. Section 3 reviews known differences between economic and engineering control problems (dependence of models of the economy on changes of government policies; time inconsistency). Section 4 adds some arguments to the debate on causality and manipulability. In systems theory the distinction between systems inputs actually used as controls and systems inputs left as disturbances is clearly determined, and the effectiveness of the control variables to drive the system on target is established. In economics, in addition to target indeterminacy, it is often unclear which variable is actually used for policy. These questions do not seem to be adequately addressed with Granger causality tests, which in fact relate to causality in prediction and not to causality in control - a concept yet to be developed. Finally, Section 5 discusses the possibility of using the well-accepted empirical fact that many macroeconomic variables appear to be integrated of order one (that is, their changes are stationary), and that some appear to be cointegrated, to the purpose of shedding some light on the problem of inferring unknown targets from available observations.

2. Target indeterminacy in economic theory

Though the controller's problem is a special case of (1), there is a different emphasis between economics and engineering. In engineering, control actions are purposefully determined with the aim of driving a given system on target. Thus, the emphasis is on the system (the physical object to control) and hence on the target. Optimality, that is the opportunity of choosing among alternative control actions, is only a *secondary* aspect of the system control problem. It is the specification of the target - in essence, the formulation of the control problem - that generates the problem of choice. Without this specification the control problem would be indeterminate, and the opportunity for choice would not occur.

In economics the emphasis is on the concept of rationality of behavior, that is on the agent's ability to establish a complete, transitive ranking among available alternatives. Economic rationality is identified with constrained optimality, and thus what is "system" for engineers becomes for economists simply the set of constraints that reduce the availability of alternatives. Plausibly, the different emphasis between engineering and economics stems from the fact that in engineering the system to design and/or to control is given, and the targets are established outside the domain of engineering; whereas in economics the focus is on modelling rational human behavior, in which targets - when in fact agents formulate them - are necessarily internal to the domain of investigation. It turns out that formulating targets may be an unnecessary intermediate step in the agents' ranking of available actions.

To see this, consider for example the standard intertemporal consumer problem in which consumption/saving decisions are obtained as the solution to an optimal control problem. This problem can be formulated as in (1) with no explicit definition of targets:

$$\max_{c(t)} E \int_0^\infty e^{-rt} U(c(t), w(t), A(t))\, dt \qquad (2)$$

subject to

$$A'(t) = rA(t) + w(t) - c(t)$$
$$A(0) = A_o$$
$$c(t) \geq 0 \text{ for all } t$$

where c, w, A, r are respectively consumption (the decision), income (the disturbance), asset capital (the outcome), and the interest rate; A' is the first time derivative of A.

Alternatively, as discussed for instance in Ermini [1988], a notion of target - and correspondingly of a target-oriented control problem in the sense of Figure 1 - can be introduced by decomposing the overall intertemporal choice problem (2) into a two-level hierarchy of subproblems. If A_T denotes asset capital at time $T< \infty$, the performance criterion in (2) can be rewritten as

$$E \int_0^T e^{-rt} U(c,w,A)\, dt + E \int_T^\infty e^{-rt} U(c,w,A)\, dt.$$

This formulation indicates the existence of two decision problems coupled to each other through the definition of the intermediate target A_T. That is, problem 1:

$$\max_{c(t)} \quad E \int_0^T e^{-rt} U(c,w,A)\, dt$$

subject to

$$\begin{aligned} &A'(t) = rA(t) + w(t) - c(t) \\ &A(T) = A_T \\ &A(0) = A_o \\ &c(t) \geq 0 \text{ for all } t\ , \end{aligned}$$

and problem 2 which is identical to (2) except for the limits of integration.

For any given value of A_T the two problems can be solved separately. In particular, the first problem becomes a target-oriented control problem. (Several intermediate targets A_i, $i = 1,\ldots, m$, could be introduced, but the extra structure would not add clarity.)

To ensure that the corresponding optimal solutions are the same as from (2), the value A_T must be properly chosen. This is accomplished by solving a "coordination" problem of target determination of the type

$$\max_{A_T} \quad V_1(A_T) + (1+r)^{-T}\, V_2(A_T)$$

subject to appropriate constraints. Here $V_i(A_T)$, $i = 1,\ 2$, are the optimal values of the utility from problem 1 and 2; the maximand is the indirect utility of the target.

In other words, the compact problem (2) can be replaced by a two-level hierarchy of subproblems: the higher-level subproblem determines the optimal target value by maximizing the indirect utility function of targets. The lower-level contains a sequence of two subproblems, of which the first is a target-oriented control problem and determines the optimum consumption path for a given future value of asset capital.

A similar example of decomposition can be based on the upper-level sub-problem determining a bliss value of consumption for the entire life-cycle, and on the lower-level sub-problem stabilizing actual consumption along this bliss value. Again, the lower-level reflects the scheme of Fig. 1.

As argued in the cited reference, though such decompositions have an interesting (potential) appeal as propositions of consumers' behavior, they become redundant - in the context of economic rationality - without costs of decision-making or costs of decision implementation. In the absence of these costs, a rational agent has no need to determine intermediate capital targets or bliss values in order to plan life-cycle consumption: alternative actions can be directly ranked through the utility function as in (2), without making them conditional on targets or on levels of bliss. It follows, for example, that all models of consumption stabilization that have appeared in the literature must be viewed as incomplete models of consumption behavior: they correspond to an incomplete two-level hierarchy, as the upper-level problem of determining the optimal bliss value is missing.

In conclusion, in consumer theory there is no role for the concept of target, unless consumers can be decomposed, by virtue of costs of decision-making, into short-run automatic controllers (or stabilizers) and long-run planners. This conclusion, of course, holds for any intertemporal choice problems, and therefore it applies to firm's and government's dynamic models as well.

Another example of how the concept of target can have a role in economic theory is offered by producer theory. In fact, the decomposition between long-run planning and short-run target-oriented control is imbedded in the theory of the firm through the identification of the cost function, without appealing to costly decision-making. Firm's decisions are obtained by solving the following problem (it could be formulated as a dynamic problem without affecting the nature of the discussion):

$$\max p(q)\, q - c(q)$$

where q is output quantity, $p(q)$ is the demand function and $c(q)$ is the cost function. The solution to this problem is not the producer's *action*, but indeed the producer's *target*. The producer's action is in fact to choose factors m so to achieve the optimal production plan. Conceptually, this latter problem reflects the control scheme of Figure 1. Thus, by virtue of the cost function $c(q)$, the firm's problem is decomposed into the "manager's problem" of planning production and into the "control engineer's problem" of achieving the planned production level despite external disturbances.

The government case is conceptually similar to the consumer case, though the examples of incomplete system control problems are more common. On the one hand, the literature abounds with models where alternative policies are directly ranked through a global welfare function - for example, the utility of a representative consumer, as often adopted in the analysis of fiscal policy (for a survey, see Aschauer [1988]). On the other hand, the literature also abounds with models where government policy is the choice of actions to achieve or stabilize exogenously given targets, along the scheme of Figure 1. For the same reasons seen in the consumer case, these target-oriented problems of control or stabilization correspond to an incomplete two-level hierarchy of models, in which the upper-level problem of target determination is missing. Economic theory, in fact, offers few insights on how the government establishes or should establish its targets, and few insights on which economic variable should be targeted. For a recent contribution to this problem, see McKibbin *et al* [1987]. (Incidentally, since the government problem does not seem to possess special features that make system control theory more suitable to it than to consumer or producer theory, the common understanding that government policy problems are the natural recipients of system control theory is probably the result of the scheme of Figure 1 being traditionally more easily recognizable in government behavior than in consumer behavior.)

Remaining in the area of government policy, an imperfect knowledge about government targets generates several problems and some confusion in the attempt to apply system control theory to government policy-making. In one instance, the imperfect information held by the public about government targets, apart from offering an interesting case of asymmetric information for the analysis of the repeated game between government and the public, prevents disentangling the estimation of the controller from the estimation of the controlled economy. The necessity of knowing the targets in order to interpret macroeconometric models is compellingly discussed, among others, in Nickell [1985].

Another issue is a degree of confusion between the normative and the descriptive purpose of solving government control problems; that is, the issue of whether control problems are solved to design government policies, or to interpret observed government behavior. Apart from institutional considerations, the idea of an incomplete two-level hierarchy for government behavior can rest on some appealing descriptive grounds: only the lower level task of control and/or stabilization can be formally modelled as economic rational behavior, as the upper-level task of target determination seems to be more often carried out through rules of thumb, past experiences, political bargaining, etc., which all escape formalization within the current received theory.

In this regard, however, it seems that rules of thumb or incomplete control schemes - for instance, schemes with no feedback - still prevail in the literature at the lower-level of policy-making as well. Examples are the two main menus available to drive the economy to full employment. The Keynesian menu suggests a high tax rate and a low money growth rate in period of booms, and vice-versa in periods of recession. The Friedman menu suggests money supply growth at a constant rate, consistent with an (average) desired level of inflation, and suggests a fiscal policy such as to generate over the business cycle a desired average level of deficit.

Another problem associated with the lack of theories about target determination is the existence of many possible targets, and the corresponding problem of choosing which policy instrument for which target. Rules of thumb abound in this area too. For example, untill the early sixties it was common practice to view fiscal policy as the instrument to control full employment, monetary policy to control economic growth, and exchange rate to control the balance of payments, with no sensible aknowledgment of possible cross-effects among instruments, or possible side-effects on other economic variables (for further discussions, see Swan [1960], Currie [1985], Vines [1987]). Incidentally, the existence of many targets, of which some may not be explicitly stated in formal models, could be partly responsible for differences in menus. This view adds an extra insight to the commonly held view that differences in Keynesian and Friedman menus are only due to a fundamental disagreement over what is the correct model of the economy, and particularly over what is the correct agents' mechanism of expectations formation (for example, Sargent [1979]).

Another problem in the applicability of system control theory to government policy-making stems from a confused recognition of the existence of a hierarchical order among targets. For example, once the policy of setting money growth at a constant rate is decided upon (to achieve, say, a specified target of inflation rate), a subordinate "servomechanism" must be set up to achieve the desired money growth rate. The control scheme of Figure 1, thus, can assume a rather complicated structure, with several control actions nested into one another in *cascade*. Figure 2 reports the cascade structure corresponding to the case discussed in Litterman [1983]: in order to reduce the inflation rate r, money growth rate is set at a desired value m, achieved by forcing the Federal Fund rate to a specific value i, which in turn is achieved manoeuvring the supply of federal funds through open-market operations.

It seems quite reasonable to believe that the methods developed by engineers in designing control structures in cascade could be usefully transferred to this and other similar cases. Consider, for instance, such important issues for policy-makers as the frequency and/or the timing of control actions (at any level of the cascade), or the coordination of performance criteria (for instance, as in Litterman, a trade-off between achieving the target m exactly and reducing the volatility of the Federal Fund rate).

Similarly, it seems reasonable to believe that system control theory can also contribute to solve other problems mentioned above. However, it is important to keep in mind that, given target indeterminacy, system control theory can only contribute to analyze *incomplete* models of government behavior, where targets are exogenously set. In this respect, system control theory is a tool for normative policy-making: it addresses questions of what policy should be enforced and how and when, for a given specific set of targets.

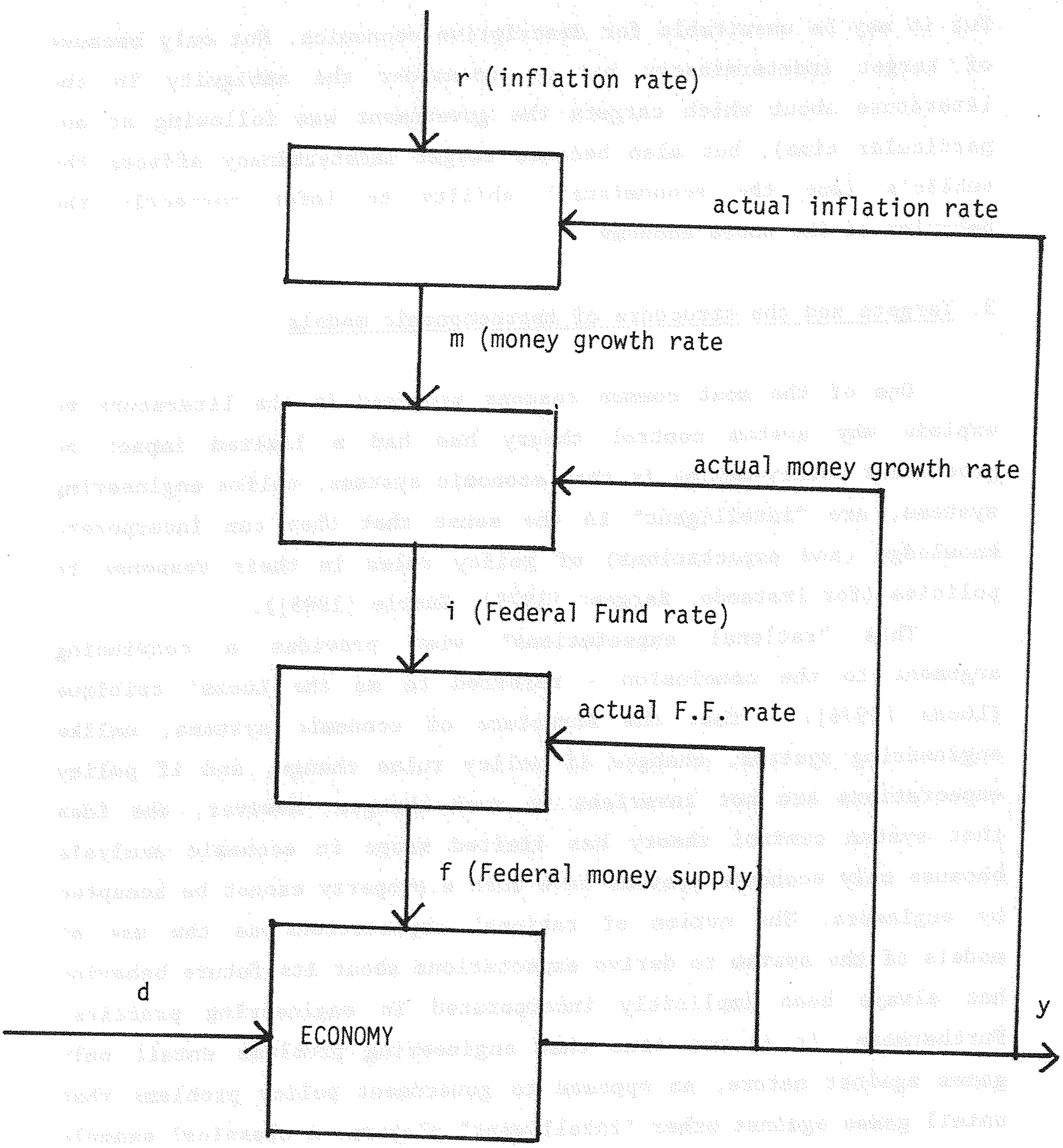

FIGURE 2 - A cascade of control schemes for monetary policy

But it may be unsuitable for descriptive economics. Not only because of target indeterminacvy *per se* (consider the ambiguity in the literature about which targets the government was following at any particular time), but also because target indeterminacy affects the public's (and the economists') ability to infer correctly the behavior of the whole economy.

3. Targets and the structure of macroeconomic models

One of the most common reasons proposed in the literature to explain why system control theory has had a limited impact on government policy-making is that economic systems, unlike engineering systems, are "intelligent" in the sense that they can incorporate knowledge (and expectations) of policy rules in their response to policies (for instance, Sargent [1979], Currie [1985]).

This "rational expectations" view provides a convincing argument to the conclusion - referred to as the Lucas' critique (Lucas [1976]) - that the structure of economic systems, unlike engineering systems, changes if policy rules change, and if policy expectations are not invariant to such changes. However, the idea that system control theory has limited scope in economic analysis because only economic systems have such a property cannot be accepted by engineers. The notion of rational expectations as the use of models of the system to derive expectations about its future behavior has always been implicitly incorporated in engineering practice. Furthermore, it is not true that engineering problems entail only games against nature, as opposed to government policy problems that entail games against other "intelligent" players. A classical example is the gun-guidance system of anti-aircraft defence.

In effect, the reason that economic systems are intelligent and engineering systems are not should be replaced by the reason that in engineering the targets are well specified, whereas in economics government targets (to remain in the area of government behavior) are often ambiguous, elusive and ill-perceived. In the example of the gun-guidance system, both players know that the system's target is to destroy the oncoming aircraft. In the government case, the public may have difficulties in knowing whether at a particular point of time the government target is employment, or the inflation rate, or the trade deficit, or exchange rate volatility, or even defence spending, etc., or some of the above suitably coordinated.

Since the structure of the economic system depends on which target is perceived by the public to be behind a given policy, a change in perception about targets leads to a change of structure. This property of economic systems, then, derives more from a confusion about targets (and hence from a confusion about policies) than from an alleged "intelligence" of economic systems in contrast to engineering systems.

The following is an example of how two different perceptions about monetary policy can affect agents' behavior (see Currie [1985] for further discussion): if money growth is perceived to be targeted on a specific rate, then when the actual money rate overshoots the target, the exchange rate will appreciate because agents know that the money supply will soon be reduced in order to bring the money growth rate down on target. This increases the interest rate, which in turn appreciates the exchange rate. On the other hand, if money growth is perceived to be non targeted to a specific value (for instance, it is perceived to be irreversible), then the resulting price increase will be viewed as permanent, and consequently the exchange rate will depreciate. As another example, the permanent income hypothesis of consumption behavior offers a case of how consumption can react differently to a change in tax rate, according to whether this change is perceived as permanent or transitory. In the first instance, the permanent income would be affected to a much larger extent, and hence consumption would too.

These different perceptions can be the result of a lack of knowledge by the public about which targets the government is actually pursuing. This asymmetry of information about targets could be purposefully sought after by the government itself, if one subscribes to the modern view of rational expectations theorists whereby, for example, the monetary authority can influence the real economy only if it has some extra information that is not available to the public. If this view is accepted, it follows that the main difference between economic and engineering systems - elusiveness of targets - does not rest on an intrinsic structural property of economic systems, but stems from a purposeful government strategy aimed at having an effective role in the economy.

Finally, the dependence of economic systems on policy changes raises the important issue of inconsistency of optimal policies - or equivalently of sub-optimality of consistent policies - as discussed particularly in Kydland and Prescott [1977] and Prescott [1977]. Briefly, a consistent policy is the optimal policy for a given current situation. It can be shown that, if the economic system depends on future policies (for instance, through expectations), this policy is in general different from the optimal policy evaluated in the past for the same time period. Therefore, there is an incentive to renege on previously determined policies; that is, these policies are inconsistent.

As argued in the cited references, the incentive to renege optimal plans can contribute to economic instability, or make a stable economy unstable. Given the viewpoint of this paper, however, it should be noticed that the literature in this field assumes that agents know both the targets and the policy instruments adopted by the governing authority. The effect of target indeterminacy, or of uncertainty about instruments, on time inconsistency, if any, have not yet been explored.

4. Manipulability. and causality

Manipulability is used here to mean the ability of the controller to affect a system variable through changes of other system variables. Causality is intended in the Granger sense, as defined and discussed in Granger [1969] and Granger [1980]. For a brief review of the concept of Granger causality, suppose that we are interested in assessing whether an economic time series x_t "causes" another series y_t. In the Granger sense, x_t causes y_t if it contains unique information about future values of y_t which is not available in other economic time series. Thus, Granger causality is a relation of *predictive* power, conditional on specific information sets. Let J_t be the information set containing past and present values of y_t and other economic variables, but not of x_t. Let J_t' be the set containing also past and present values of x_t. J_t' could be the universal information set. Let $f(y_{t+n}|J_t)$ be the conditional probability distribution of y_{t+n} given J_t. Then:

(i) x_t does not cause y_{t+n} with respect to J_t if

$$f(y_{t+n}|J_t) = f(y_{t+n}|J_t')$$

(ii) x_t is a "prima facie" cause of y_{t+n} with respect to J_t if

$$f(y_{t+n}|J_t) \neq f(y_{t+n}|J_t').$$

The qualification "prima facie" reflects the possibility that, by enlarging the information set J_t with inclusion of more variables, the causality of x_t disappears. Of course, if x_t does not cause y_{t+n} with respect to J_t, it will not cause it with respect to any enlarged information set. To make these definitions operational, it is customary to restrict the attention to the first moment of the distribution, so that

(iii) x_t does not cause y_{t+n} in mean with respect to J_t if

$$E[y_{t+n}|J_t] = E[y_{t+n}|J_t'] \tag{3}$$

(iv) x_t is a "prima facie" cause in mean of y_{t+n} with respect to J_t if

$$E[y_{t+n}|J_t] \neq E[y_{t+n}|J_t']. \tag{4}$$

It is also customary to limit the definition of causality to the next-period value, y_{t+1}. This is also done here, so that definitions (3) and (4) applied to y_{t+1} will be simply referred to as "x Granger causes y". It is important to note that if x_t is a deterministic function of some of the series in J_t, then it does not cause y.

This definition of causality is, of course, controversial. For a review of the criticism and a defence, see Zellner [1979] and Granger [1980]. Its misuse can lead to paradoxical cases of spurious causality, as for example the case discussed in Granger [1980] of lightning and thunder: since lightning helps predict the occurrence of thunder, lightning Granger-causes thunder, even if in fact the two events are generated by the same (unobserved) cause at different times.

A typical case of misuse of the concept of causality is when it is ambiguously interpreted as physical causation, even if empirically tested in the limited and specific context of Granger's definition. Examples of this ambiguity in economics are government policy studies where tests of Granger causality are mistaken for tests of policy effectiveness (that is, of manipulability). To establish the relation between manipulability and Granger causality, suppose that the true model of the economy is

$$y = f(x_1, \ldots, x_n) \tag{5}$$

in the sense that any change in a single variable of $X = (x_1, \ldots, x_n)$ changes y, but any change in any variable contained in the complement set of X does not. So, X is the set of "physical" causation. The variables in this set are the variables that enter the agents' decision rule, including mechanisms of expectations formation. (A parallel example from physics would be that pressure is a physical causation of the boiling temperature of liquids, in that a change of the former affects the latter.) Manipulability is obviously associateed with X: a controller having the ability to set some of the x's at will has the ability to affect y.

Instead, Granger causality is associated with the econometric model that economists can build for (5), of the type

$$y = g(z_1, \ldots, z_m) + u \tag{6}$$

where $Z = (z_1, \ldots, z_m)$ is the set of exogenous observed variables, and u is a stochastic error which captures, *inter alia*, the effect of not observing some of the x's, the fact that g usually belongs to a restricted class of functions for mathematical tractability, the randomness introduced by aggregating over agents, etc. Since the z variables are included in $g(.)$ only on a purely statistical basis (correlations), Granger causality is obviously associated with the set Z.

It is easy to see that the set Z does not contain the set X, nor is it contained by it. Thus, in general, Granger causality is not a sufficient nor a necessary condition for physical causality. Moreover, physical causality does not imply manipulability, as only some of the variables in X are in general available to a controller. An example of a variable of physical causation that is not present in Z is the case of common factors, as discussed in Granger [1984]: the decision rule (5) usually contains a number of agent-specific variables, such as age, occupation, education, location, sex, race, etc; and a number of factors common to all agents, such as interest rates, tax rates, publically announced forecasts, etc. Granger shows that under certain circumstances, when aggregating individual decision rules over the entire population, the statistical relevance of some individual factors may disappear. Thus, physical causality does not imply Granger causality.

A case of a variable of Granger causation that is not present in X is the previous example of lightning and thunder: the relation of spurious causality between lightning and thunder is due to the existence of a common cause. Another example of common cause, cited in Kalman [1982] in a different context, is offered by the biologist Francis Galton who found a very high correlation between fathers' height and sons' height. Whereas the great predictive power of fathers' height for sons' height would allow one to conclude that the former causes the latter in Granger sense, it is certainly not true that the former is a physical causation of the latter.

Incidentally, in both examples it is possible to dismiss spurious causality as a case of unobserved common cause only because some extra structure, or some extra knowledge, is available to the investigator. For example, the knowledge of the physical process of electrical discharge in the case of lightning and thunder, or the knowledge of the process of transmission of genetic codes linked to human height. If all the z variables not included in X were found to be caused by some subset of X (including some unobservable x's) - for instance, because some extra knowledge is available to recognize the presence of common causes - then Granger causality would imply physical causality. However, for example, the literature on the effects of sun spots on the real economy shows that, under specific circumstances, predictions based on wrong Granger causal relationships can be fulfilled, thus demonstrating that sun spots - which of course cannot be caused by any x - belong to Z but not to X. Thus, Granger causality does not imply physical causality.

Another argument against the use of Granger causality tests for policy effectiveness is that feedback control schemes destroy the link - if any - between manipulability and Granger causality. To discuss this issue, suppose that the true model of the economy (the system S of Figure 1) is

$$y_t = a\, y_{t-1} + b\, m_{t-1} + c\, x_{t-1} + u_t \qquad (7)$$

where u_t is a white noise disturbance, m_t and x_t are system inputs, and y_t is the system output. Suppose also that the public knows that the government policy instrument is m and not x; that is, in terms of Figure 1, $d_t = [u_t, x_t]$. Notice the time lag at which system inputs affect the output: in (7) it is implicitly assumed that physical causality cannot be instantaneous. (For a discussion on the plausibility of this assumption in a discrete-time framework, see Granger [1980b] and Granger [1985]). It is also assumed that the economy consists only of government and public, and that whatever action the government takes, it will not affect the structure of the economy. Finally, it is also assumed, without loss of generality, that if an agent observes the three series y_t, m_t, x_t, the parameters of the economy can be estimated without error.

Suppose the government has a target r_t for y_t, and determines at time t-1 the value of the control m_{t-1} so to minimize the quadratic deviations of output from target. Then the optimum control would be:

$$m_{t-1} = - b^{-1}[a\ y_{t-1} + c\ x_{t-1} - r_{t-1}] \tag{8}$$

where r_{t-1} indicates that the government knows the target for y_t at time t-1. By implementing (8) we get:

$$y_t = r_{t-1} + u_t\ . \tag{9}$$

Equations (8) and (9) form the basis for the criticism against the use of Granger causality tests in control situations (see, among others, Sims [1972], Sargent [1976] and Buiter [1984]). For any agent having access to the information set $\{y_{t-j}, x_{t-j}, r_{t-j}, j\geq 1\}$, the control m cannot possibly appear as a Granger-cause of y because (8) is a deterministic relation. Moreover, if the target is non random (as usually assumed in the literature), then from (9) the best model for output would be a deterministic component plus white noise, observationally equivalent to (7).

The conclusion that by nature of feedback control a Granger causality test will always fail, even though the variable in question is indeed used for control, is challenged in Granger [1988]. To counteract this conclusion, Granger introduces an implementation error in the control action:

$$m_{t-1} = - b^{-1} [a y_{t-1} + c x_{t-1} - r_{t-1}] + u_{2t-1} \qquad (10)$$

with u_{2t-1} a white noise series. Consequently

$$y_t = r_{t-1} + b u_{2t-1} + u_t \qquad (11)$$

and clearly with respect to the same information set as before m_t now causes y_t in the Granger sense, since it contains, as seen from (10), unique information about u_{2t}. Incidentally, the presence of a non systematic error in policy implementation finds theoretical support in the rational expectations view that a policy to be effective must be contaminated with noise.

The main conclusion is that if a variable m is physically causing y and if it is indeed used for a feedback control action, then there may exist circumstances in which Granger causality tests fail to detect manipulability, and others in which these tests do not fail. In other words, if one knows the government target and the policy instrument actually used, then it is not necessarily true, as claimed in some literature, that Granger tests convey no information about policy effectiveness.

However, this conclusion does not address the really important questions about policy effectiveness: how can an "external" observer, such as the public, infer from the available observations whether the economy is under government control; and if so, which control variables are used, and for which target.

For example, if the public observes the same information set available to the government, $\{y_{t-j}, x_{t-j}, r_{t-j}, m_{t-j}, j \geq 1\}$, the public readily concludes that the economy is under control by regressing the equation of the economy (7) and the feedback rule (10). However, it would be impossible for the public, in the absence of extra structure, to infer whether the government is using m_t or x_t (or both) as control. With the given information, the public can estimate, instead of (10), the following feedback rule:

$$x_{t-1} = - c^{-1} [a y_{t-1} + b m_{t-1} - r_{t-1}] - b/c \, u_{2t-1}$$

and a Granger causality test would determine that x_t causes y_t with respect to $\{y_{t-j}, m_{t-j}, r_{t-j}, j \geq 1\}$, even if in fact the government is manipulating m_t. This example shows that even if Granger causality tests do not fail, they still do not convey the type of information about manipulability that one would expect in judging the effectiveness of government policies.

In conclusion, three different possibilities arise against the use of Granger tests as test of manipulability: (i) even if a specific variable m physically causes y without feedback control, it is possible that when feedback control is applied the causal relation disappears; (ii) even if a specific variable x physically causes y, it is not necessarily the one used as a control variable; (iii) it may be possible that an economic variable is chosen as policy instrument to target a certain outcome, even if in fact it does not physically cause that outcome.

A final remark relates to the importance of knowing the target r_t. Suppose the public observes all the variables in the economy, except the government target. Then the public estimates the model of the economy (7) and possibly the feedback rule:

$$m_{t-1} = - b^{-1}[a\ y_{t-1} + c\ x_{t-1}] + u_{3t-1} \qquad (12)$$

where now u_{3t} is not necessarily a white noise series. Correspondingly

$$y_t = u_{3t-1} + u_t$$

and hence with respect to the information set $\{y_{t-j}, x_{t-j}, j \geq 1\}$ the series m_t would still be seen as Granger causing y_t, since it contains unique information about u_{3t}. However, this type of Granger causality cannot be interpreted as a form of manipulability, because the public has not enough information to distinguish whether (12) is the result of a purposeful government action or it is simply an additional equation of the model of the economy, with the economy under no apparent control. Thus, when the public does not know the government target - provided there is one - Granger causality tests, even if positive, do not help in establishing whether the economy is under control or not. The public does not have enough information to disentangle the controller from the system.

5. System stability and cointegration

The fact that many important economic variable appear to be integrated of order one - that is, to have the property that their changes are stationary (integrated of order zero) - and the recent development of a concept of cointegration (Granger [1983], Engle and Granger [1987]) might provide useful insights to the problem of inferring government targets from observed macroeconomic variables.

For a brief review of concepts, y_t integrated of order one is indicated as $y_t \sim I(1)$, so that $\Delta y_t \sim I(0)$. $I(0)$ processes have bounded variance, have finite or exponentially decaying memory, and cross their mean value - say zero - in finite average time. $I(1)$ processes have a variance proportional to the time elapsed since the process started, have infinite memory, and cross their mean value in infinite average time. In general, if y_t and r_t are $I(1)$, so are all linear combinations of these variables. However, it is possible that for some processes there exists a constant b such that $(y_t - b\, r_t) \sim I(0)$. In this case, y_t and r_t are said to be cointegrated. Thus, while y_t and r_t wander around with only some very chancy crossing of the mean line, that particular linear combination is frequently zero. For this reason, cointegration is obviously associated with the notion of equilibrium in the economy: economic theory provides a reason for certain variables to be in equilibrium - that is, $y = b\, r$ - but in practice these equilibria are not attained at every period.

Cointegration can also be clearly associated with the relation between outcome and target in a control problem (with $b = 1$), provided both variables are $I(1)$. In fact, it is certainly not true that the outcome is driven precisely on target at every period. Equations (9) or (11) support this notion: if both y_t and r_t are $I(1)$, then their difference under optimal control is a white noise series. Nickell [1985] provides a broader theoretical support for this notion, by considering optimal controls based on minimizing costs of adjustments, in addition to square deviations.

On the ground that, in order to make sense, a control action must generate stationary deviations, Granger [1988] derives some necessary and sufficient conditions for the parameters of the model of the economy and of the control rule, so that y_t and r_t are $I(1)$ but their difference is $I(0)$. In particular, it is found that if the outcome of a controlled system is observed as $I(1)$, then the target must necessarily be $I(1)$ as well. This result, for example, entails that, since GNP appears to be integrated of order one, if the government is targeting GNP to full employment, then the natural rate should also follow an integrated process of order one. It is also found that in general the control variable and the outcome under control are not cointegrated.

In what follows, additional results will be derived for the special case in which the control rule is a linear function of current and past deviations only, in line with the early tradition of PDI (proportional, integrative, derivative) automatic controllers in engineering. For simplicity of notation, the reference to both disturbances x_t and u_t will be dropped. Thus, indicating with B the lag operator, that is $y_{t-1} = B\, y_t$, the control scheme is based on the two following equations:

$$y_t = P(B)\, m_t \tag{13}$$
$$m_t = C(B)(r_t - y_t) \tag{14}$$

where $P(B)$ is the model of the economy and $C(B)$ the control rule. Thus:

$$y_t = G(B)\, r_t, \qquad G(B) = P(B)C(B)/[1 + P(B)C(B)] \tag{15}$$
$$m_t = M(B)\, r_t, \qquad M(B) = C(B)/[1 + P(B)C(B)] \tag{16}$$

Firstly, consider that any instability of the economy (any root of the polynomial $P(B)$ greater or equal to one in absolute value) can be eliminated by designing a control rule $C(B)$ such to cancel unstable roots from the product $P(B)C(B)$. For example, if $r_t \sim I(0)$ and one observes y_t to be $I(0)$ as well, but economic theory says $P(B) = Q(B)/(1-B)$ with $Q(B)$ stable, then the control rule $C(B) = (1-B)C'(B)$ with $C'(B)$ stable would stabilize the overall controlled system $G(B)$.

Furthermore, suppose that both $P(B)$ and $C(B)$ are stable. Then $y_t \sim I(1) \Leftrightarrow r_t \sim I(1)$. This result clearly follows from (15). Moreover, from (16) $r_t \sim I(1) \Leftrightarrow m_t \sim I(1)$. By stationarity of $C(B)$, however, from (14) if $y_t \sim I(1)$, then $(r-y) \sim I(1)$ as well; that is, target and controlled outcome are *not* cointegrated. It follows that $(r-y) \sim I(0)$ only if $C(B) = C'(B)/(1-B)$. Notice that in this case both $G(B)$ and $M(B)$ remain stable. This result shows that if r_t and y_t are $I(1)$, then in order to stabilize the deviations between target and controlled outcome, the controller manipulates - as a linear function of the deviations - the rate of change of the controlled variable, and not its level.

For example, if the manipulated variable for GNP targeted on full employment is the government budget deficit, this result is consistent with the simple Keynesian menu of increasing deficit in periods of recession and decreasing it in periods of booms. Note that with such a control scheme, the deficit will follow an integrated process of order one, and thus will cross its zero mean value in infinite average time.

6. Conclusions

This paper discusses some old and new reasons why system control theory has had only a limited impact on economic analysis. The lack of knowledge about targets - typical of many applications in economics - emerges as the most important difference between engineering systems and economic systems. Whereas this lack of knowledge would not pose any problem in normative policy-making, it generates several problems for descriptive economic analysis. Possibly, some light on the ability to infer unknown targets can be shed by the use of some recent empirical and theoretical advancements in time-series analysis, such as cointegration.

Another problem is posed by the lack of knowledge about the policy instruments that the government is actually manipulating in any specific situation. To this regard, Granger causality tests do not seem helpful.

References

Astrom K.J., 1970, Introduction to stochastic control theory, Academic Press, New York.

Aoki M., 1978, Optimal control and system theory in dynamic economics, North-Holland, N.Y.

Aschauer P.A., 1988, The equilibrium approach to fiscal policy, Journal of Money, Credit and Banking, vol. 20, no. 1, pp. 41-62.

Buiter W.H., 1984, Granger-causality and policy effectiveness, Economica, vol. 51, pp. 151-162.

Chow G.C., 1975, Analysis and control of dynamic economic systems, Wiley, New York.

Currie D., 1978, Macroeconomic policy and government financing: a survey of recent developments, in M.J. Artis and A.R. Nobay (eds.), Studies in Contemporary Economic Analysis, vol. 1, Croom Helm.

Currie D., 1985, Macroeconomic policy design and control theory - a failed partnership?, The Economic Journal, vol. 98, pp. 285-306.

Engle R., C.W.J. Granger, 1987, Cointegration and error correction: representation, estimation and testing, Econometrica, vol. 55, no.2.

Ermini L., 1988, Hierarchical decomposition in economic analysis, Proceedings of the Fourth Annual Conference of the Society for the Advancement of Behavioral Economics (SABE), San Diego, June.

Feichtinger G., edit., 1982 , Optimal control theory and economic analysis, North Holland, Amsterdam.

Granger C.W.J., 1969, Investigating causal relations by econometric models and cross-spectral methods, Econometrica, vol.37, pp. 424-438.

Granger C.W.J., 1980, Testing for causality, Journal of Economic Dynamics and Control, vol. 2, pp. 329-352.

Granger C.W.J., 1980b, Generating mechanisms, models and causality, discussion paper no. 80-26, UCSD.

Granger C.W.J., 1983, Co-integrated variables and error-correcting models, discussion paper no. 83-13, UCSD.

Granger C.W.J., 1984, Implications of aggregation with common factors, discussion paper no. 84-17, UCSD.

Granger C.W.J., 1985, Causal testing in a decision science, discussion paper no. 85-19, UCSD.

Granger C.W.J., 1988, Causality, co-integration and control, Journal of Economic Dynamic and Control, forthcoming.

Kalman R.E., 1982, Identification from real data, in M. Hazewinkel and A.H.G. Rinnooy Kan (eds.), Current Developments in the Interface: Economics, Econometrics, Mathematics, pp. 161-196, Reidel Publishing Co.

Kydland F.E., Prescott E.C., 1977, Rules rather than discretion: the inconsistency of optimal plans, Journal of Political Economy, vol. 85, no. 3.

Litterman R.B., 1982, Optimal control of the money supply, staff report no. 82, Federal Reserve Bank of Minneapolis.

Lucas R.E., 1976, Economic policy evaluation: a critique, in K. Brunner and A.H. Meltzer (eds.), The Phillips curve and labor markets, North Holland, Amsterdam.

Lucas R.E., T.J. Sargent, eds., 1981, Rational expectations and econometric practice, University of Minnesota Press.

Martos B. 1987, Control and coordination of economic activity, in J. Eatwell, M. Milgate, P. Newman (eds.), The New Palgrave, Macmillan, London.

McKibbin W., N. Roubini, and J. Sachs, 1987, Dynamic optimization in two-party models, NBER discussion paper no. 2213, NBER, Cambridge.

Nickell S., 1985, Error correction, partial adjustment and all that: an expository note, Oxford Bulletin of Economics and Statistics, vol. 47, no. 2, pp. 119-129.

Phillips A.W., 1954, Stabilization policy in a closed economy, Economic Journal, vol. 64, pp. 290-323.

Prescott E.C., 1977, Should control theory be used for economic stabilization?, in K. Brunner and A. Meltzer (eds.), Optimal Control Theory and Technology Exports, Carnegie-Rochester Conference Series on Public Policy, 1977, pp. 13-35.

Sargent T.J., 1976, The observational equivalencies of natural and unnatural rate theories of macroeconomics, Journal of Political Economy, vol 84, no. 3, pp. 631-640.

Sargent T.J., 1979, Macroeconomic theory, Academic Press.

Simon H.A., 1952, On the application of servomechanism theory in the study of production control, Econometrica, vol. 20, pp. 247-268.

Simon H.A., 1982, Models of bounded rationality, MIT Press, Cambridge.

Sims C.A., 1972, Money, income and causality, American Economic Review, vol. 62, pp. 540-552.

Sims C.A., 1982, Policy analysis with econometric models, Brookings Papers on Economic Activity, pp. 107-164, Brookings Institution, Washington

Swan T.W., 1960, Economic control in a dependent economy, Economic Record, vol. 36, pp. 51-66.

Vines D., 1987, Stabilization policy, in J. Eatwell, M. Milgate, P. Newman (eds.), The New Palgrave, Macmillan, London.

Zellner A., 1978, Causality and econometrics, in K. Brunner and A.H. Meltzer (eds.), Three Aspects of Policy and Policy Making: Knowledge, Data and Institutions, North Holland, Amsterdam.

Working Papers in Economics

60.	J. Yates	Access to Housing Finance and the Campbell Report: The Implication of Implementing the Recommendations of Chapter 37; July 1982
61.	S.S.Joson	The Gatt Agreement on Government Procurements: Canada and Australia; July 1982
62.	R.T. Ross	General Report of the 1980 Survey of Work Patterns of Married Women in the Sydney Metropolitan Region; July 1982
63.	W.J. Merrilees	Pension Benefits and the Decline in Elderly Male Labour Force Participation; September 1982
64.	W.P. Hogan	Industry,Employment and Inflation; October 1982
65.	A.J. Phipps	Australian Unemployment: Some Evidence from Industry Labour Demand Functions; November 1982
66.	E.M.A. Gross & W.P. Hogan	Short Term Management of the Australian Exchange Rate, 1977-82; December 1982
67.	V.B. Hall	Industrial Sector Interfuel Substitution Following the First Major Oil Shock; January 1983
68.	J. Yates	Access to Housing Finance and Alternative Forms of Housing Loans in the 1980s; July 1983
69.	V.B. Hall	Major OECD Country Industrial Sector-Interfuel Substitution Estimates: 1960-79; August 1983
70.	F. Gill	Inequality and Arbitration of Wages in Australia: An Historical Perspective; December 1983
71.	W.J.Merrilees	Do Wage Subsidies Stimulate Training? An Evaluation of the Craft Rebate Scheme; November 1983
72.	M.C. Blad	Economic Policy and Catastrophe Theory; November 1983
73.	C.G.F. Simkin	Does Money Matter in Singapore?; April 1984
74.	J. Yates	Home Purchase Assistance for Low Income Earners; March 1984
75.	C.G.F. Simkin	Long-term Aspects of New Zealand's External Deficits; April 1984
76.	C.G.F. Simkin	Methodological Scepticism; July 1984
77.	V.B. Hall	Industrial Sector Fuel Price Elasticities of Demand Following the First and Second Major Oil Shocks; August 1984
78.	S.S. Joson	Substitutability of 'Buy Local' Policy for Tariff Protection in Small Economies; January 1985
79.	R.T. Ross	Analysis of the 1980 Sydney Survey of Work Patterns of Married Women: Further Results; January 1985
80.	J. Yates	Discrimination in Lending; May 1985
81.	R.T. Ross	Measuring Underutilisation of Labour: Beyond Unemployment Statistics; May 1985
82.	P.D. Groenewegen	Alfred Marshall as Professor of Political Economy at Cambridge 1885-1908; June 1985
83.	C.G.F. Simkin	Popper's Methodology and Economic Theory; July 1985
84.	E.M.A. Gross, W.P. Hogan & I.G. Sharpe	Market Information and Potential Insolvency of Australian Financial Institutions; July 1985
85.	F. Gill	Over-Award Payments; Result of a Survey conducted in 1982; December 1985
86.	S.K. Kim	Short Run Policy Analysis of Employment, Food Price and Rural-Urban Migration for a Labour-Abundant Developing Economy; January 1986
87.	E. Kiernan & D.B. Madan	Stochastic Stability in a Rational Expectations Model of a Small Open Economy; March 1986
88.	E. Gross	A Note on the Testability of Fama's Efficient Capital Market Hypothesis; February 1986
89.	M.C. Blad & E. Gross	Multinational Producers in an Arrow-Debreu type General Equilibrium Model; March 1987
90.	P. Saunders	Explaining International Differences in Public Expenditure: An Empirical Study; August 1986

91.	W.P. Hogan	International Debt and Foreign Exchange Markets; January 1987
92.	Michael C. Blad & Nicholas Oulton	Union-Firm Bargaining as a Repeated Prisoner's Dilemma; January 1987
93.	R.T.Ross	The Heckman Procedure for Estimating Static Disaggregate Labour Supply Functions: An International Comparison of Estimates for Married Women; March 1987
94.	W.P. Hogan	Assessing Insider Trading; June 1987
95.	J. Yates	Housing Policy Reform: A Constructive Critique; June 1987
96.	B.W. Ross	The Leisure Factor in Entrepreneurial Success during the 'Robber Baron' Era; July 1987
97.	F. Gill	Determination of Wage Relativities under the Federal Tribunal: 1953-1974; August 1987
98.	A.J. Phipps	Union Objectives, Wage Bargaining and the Phillips Curve; October 1987
99.	R.T. Ross	The Labour Market Position of Aboriginal People in New South Wales; November 1987
100.	L. Haddad	List Revisited: Dynamic Consideration of Trade and Protection; November 1987
101.	John Piggott	General Equilibrium Computation Applied to Public Sector Issues; December 1987
102.	J.A. Carlson & D.W. Findlay	Relative Prices, Wage Indexation and Unemployment; December 1987
103.	M. Waterson	A Model of Product Differentiation and Profitability; December 1987
104.	P.D. Groenewegen	Taxation and Decentralisation: A Reconsideration of the Costs and Benefits of a Decentralised Tax System; March 1988
105.	L. Ermini	Some New Evidence on the Timing of Consumption Decisions and on Their Generating Process; March 1988
106.	G. Mills	Spatially-Differentiated Trucking Markets: Equilibria under Price Regulation without Entry Restrictions; April 1988
107.	B.W. Ross	Strategic Commitment, Unknowledge and the Nature of Entreprenuerial Activity; April 1988
108.	S.S. Joson	Offsets and Development of Defence Support Industries in Small Economies; April 1988
109.	B.W. Ross	The Conglomerate and the Focussed Agglomerate: Modern Forms of the Leader-Commanded Firm; July 1988
110.	L. Ermini	Inertial Behavior on Schedule and Hierarchical Decomposition; July 1988
111.	L. Ermini	The Limits of Systems Control Theory in Economic Policy-Making; July-October 1988

Copies are available upon request from:

Department of Economics,
The University of Sydney,
N.S.W. 2006, Australia.

Working papers in Economics Published or Accepted for Publication Elsewhere

2.	I.G. Sharpe & R.G.Walker	Journal of Accounting Research, Vol. 13, No.2, Autumn 1975
3.	N. V. Lam	Journal of the Developing Economies, Vol. 17, No.1, March 1979
4.	V.B. Hall & M.L. King	New Zealand Economic Papers, Vol. 10, 1976
5.	A.J. Phipps	Economic Record, Vol. 53, No. 143, September 1977
6.	N.V. Lam	Journal of Development Studies, Vol. 14, No. 1, October 1977
7.	I.G. Sharpe	Australian Journal of Management, April 1976
9.	W.P. Hogan	Economic Papers, No. 55, The Economic Society of Australia and New Zealand
12.	I.G. Sharpe & P.A. Volker	Economics Letters, 2, (1979)
13.	I.G. Sharpe & P.A. Volker	Kredit and Kapital, Vol. 12, No.1, 1979
14.	W.P. Hogan	Some Calculations in Stability and Inflation, A.R.Bergstrom et.al. (eds), John Wiley and Sons, 1978
15.	F. Gill	Australian Economic Papers, Vol. 19, No. 35, December 1980
18.	I.G. Sharpe	Journal of Banking and Finance, 4, 1980
21.	R.L. Brown	Australian Journal of Management, Vol. 3, No. 1, April 1978
23.	I.G. Sharpe & P.A. Volker	The Australian Monetary System in the 1970s, M. Porter (ed.), Supplement to the Economic Board 1978
24.	V.B. Hall	Economic Record, Vol. 56, No. 152, March 1980
25.	I.G. Sharpe & P.A. Volker	Australian Journal of Management, October 1979
27.	W.P. Hogan	Malayan Economic Review, Vol. 24, No. 1, April 1979
28.	P. Saunders	Australian Economic Papers, Vol. 19, No. 34, June 1980
29.	W.P. Hogan I.G. Sharpe & P.A. Volker	Economics Letters, 6 (1980)
29.	W.P. Hogan I.G. Sharpe & P.A. Volker	Economics Letters, 7 (1981)
30.	W.P. Hogan	Australian Economic Papers, Vol. 18, NO. 33, December 1979
38.	U.R. Kohli	Australian Economic Papers, Vol. 21, No. 39, December 1982
39.	G. Mills	Journal of the Operational Research Society 33, (1982)
41.	U.R. Kohli	Canadian Journal of Economics, Vol. XV, No. 2, May 1982
42.	W.J. Merrilees	Applied Economics, Vol. 15, February 1983
43.	P. Saunders	Australian Economic Papers, Vol 20, No. 37, December 1981
45.	W.J. Merrilees	Canadian Journal of Economics, Vol. XV, No. 3, August 1982
46.	W.J. Merrilees	Journal of Industrial Economics, Vol. XXXI, March 1983
49.	U.R. Kohli	Review of Economic Studies, Vol. L(1) No. 160, January 1983
50.	P. Saunders	Economic Record, Vol. 57, No. 159, December 1981
53.	J. Yates	AFSI, Commissioned Studies and Selected Papers, AGPS, IV 1982
54.	J. Yates	Economic Record, Vol. 58, No. 161, June 1982
55.	G. Mills	Seventh Australian Transport Research Forum-Papers, Hobart, 1982
56.	V. B.Hall & P. Saunders	Economic Record, Vol. 60, No. 168, March 1984
57.	P. Saunders	Economic Record, Vol. 59, No. 166, September 1983
58.	F. Gill	Economie Appliquee, Vol XXXVII, 1984, No's 3-4, pp. 523-541
59.	G. Mills & W. Coleman	Journal of Transport Economics and Policy, Vol. XVI, No. 3, September 1982
60.	J. Yates	Economic Papers, Special Edition, April 1983
61.	S.S. Joson	Australian Economic Papers, Vol. 24, No. 44, June 1985

62.	R.T. Ross	*Australian Quarterly*, Vol. 56(3), Spring 1984
63.	W.J. Merrilees	*Economic Record*, Vol. 59, No. 166, September 1983
65.	A.J. Phipps	*Australian Economic Papers*, Vol. 22, No.41, December 1983
67.	V.B. Hall	*Economics Letters*, 12, (1983)
69.	V.B. Hall	*Energy Economics*, Vol. 8, No. 2, April 1986
70.	F. Gill	*Australian Quarterly*, Vol. 59, No.2, Winter 1987
71.	W.J. Merrilees	*Australian Economic Papers*, Vol. 23, No. 43, December 1984
74.	J. Yates	*Australian Quarterly*, Vol. 56 (2), Winter 1984
77.	V.B. Hall	*Economics Letters*, 20, (1986)
78.	S.S. Joson	*Journal of Policy Modeling*, Vol. 8., No. 2, Summer 1986
79.	R.T. Ross	*Economic Record*, Vol. 62, No. 178, September 1986
81.	R.T. Ross	*Australian Bulletin of Labour*, Vol. 11(4), September 1985
82.	P.D. Groenewegen	*History of Political Economy*, vol. 20(4), Winter 1988