ON MAN AND MACHINE

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Introduction

The machine ows its existence to the man. Nonetheless, the man was always impressed by this product of his creativity. Building artefacts which are meant to duplicate human activities, the man had hidden hopes that the machine will contribute to better understanding of himself or even go beyond the constraints of biological systems. The main goal of this lecture is to discuss to what extent such expectations are justified having in view the advances in artificial intelligence (AI), robotics and rehabilitation engineering. To be more specific, the object of our deliberations will be the following issue:

Is it possible to get a better insight into the neural control by studying skill based AI systems?

Early Cybernetic Approach

First attempts to arrive at a general view on the man and the machine were under heavy impact of advances in control engineering, communication theory and computer science /1/. Currently, robotics must be added to this list of advanced engineering research.

No matter how impressive the advances in the above mentioned engineering fields have been, it is fair to say that they were unable to serve as the scientifically viable background for the study of control and communication in the man and the machine. However, it would be wrong to assert that our understanding of the man-machine relation did not undergo deep changes in the meantime. At least, we know which biological phenomena are beyond the reach of the mathematical system and control theory, and what are the reasons for this failure /2, 3/.

The extension of the state space approach to nonlinear, multivariable dynamic systems arose hopes that the same mathematical tools could be applied to multilevel, multigoal optimisation problems. With some exceptions, this proved to be incorrect. Formal methods, aimed at numerical solutions of large system problems, simply cannot handle complex hierarchical dynamic structures. Basic features of the biological world, such as self organisation, selfadaptation, language generation, locomotion under the most awkward environmental conditions, etc., are out of reach of the state space methods and computer science. In other words, a general theory on control and communication in the man and the machine cannot be developed by extending machine principles to biology.

In order to support the above statement, some general principles pertinent to the engineering control and finite automata (computers) will be recalled:

1. Any future state of the dynamic system can be derived on the basis of the current state and the known input function.

2. The output of the finite automaton is determined by its initial state, input sequence of symbols and the internal state of the machine.

Foundations of mathematical system theory are based on the above assumptions. When interpreted in a less formal way, they simply state that

a. the future behaviour of machines, without stored programs, is affected only by their past history;
b. all machines, with and without internal memory, can be forced to repeat, as many times as desired, each of their past states.

This is due to the fact that computer memories are erasable. In other words, one can destroy the memory content without destroying the machine itself. Evolution of biological systems follows just the opposite pattern. The whole time history affects their response, and they can be never brought back to previous states. The destruction of their memory means the destruction of the object itself.

In addition to the above general features of machines, there are other properties of mechanical dynamical systems which make them basically different from biological objects. But, this is not the main topic of the lecture. The point made here is that man-machine relations must be explored in a comprehensive and critical way in order to benefit fully from multidisciplinary interaction. AI (artificial intelligence) approaches are quite promising in this regard.

AI Methodology

Early hopes that the potential of programmable machines could be easily stretched out to deal with high level functions of the man such as language understanding, translation, skill acquisition, etc., did not meet optimistic expectations. In order to overcome this state of affairs, a new avenue of research in the study of intelligent behaviour in the man and the machine was proposed. Artificial intelligence approach is not concerned with the extension of machine theory and numerical solutions to the biology. Instead, it explores the ways how human cognitive activities and expertise may be transferred to the machine in such a way that, starting from the initial data, the machine may improve its performance. Theoretical value of this research tool is based on the assumption that in the process of transferring and representing the knowledge in the machine, we can get a better insight in the functioning of the neural system.

The assessment of overall AI contribution to improved understanding of man-machine relation is outside the scope of this lecture. A specific AI research field represents the object of our interest. It is the firm belief of the author that by transferring and representing motor reflexes and motor skills in the machine, we shall be able to get important insight into the nature of the neural system. Definite conclusions cannot be made since the study of skill based AI systems is at its early stages. However, current research in reflex control of medical and industrial robots looks quite promising.

In this context, the term reflex refers essentially to monosynaptic, non-modulated sensory driven motor activity. As shown below, even the transfer and the representation of such a rudimentary motor action may throw interesting light on the deep difference between the control in the man and the machine. The term "motor skill" refers here to sensory driven functional motions made automatic by learning and training.

Reflex Representation in the Machine

Control of assistive devices for the locomotion of handicapped using artificial reflexes is becoming a promising trend in medical robotics /4/. Based on this approach, a new method of rehabilitation engineering is being introduced, the so-called hybrid assistive systems which are controlled in parallel by biological and artificial reflexes /5/.

Designing of reflex controlled machines requires the solution of the following two problems: the identification of transferable features of biological reflexes, and representation of thus derived knowledge in the machine /4/. In accordance with the main goal of the lecture, we shall point out to certain conclusions which can be derived about the nature of the simplest type of biological motor reflexes on the basis of AI studies of reflex controlled machines.

Let us take as an example, the pain evasion action triggered off by touching a hot spot. How can such reflex action be represented in the machine ? The artificial reflex loop controlling the equivalent functional motion in the anthropomorphic robot arm cannot, naturally, simulate all the internal neuromuscular mechanisms involved in the biomechanical response of the man. In order to reproduce the same reflex action in the machine, we need to trigger off only the same input-output mapping.

In this specific case, a heat detection sensor is needed and a stored control vector reproducing evasive motion of the manipulator with maximum allowed speed. The next step is to bring the manipulator to a stop, i.e. to the desired end position, once the output of the heat sensor has returned to nominal value. Formal general description of the above reflex leads to expressions of the following type

$$B(x_1,x_2,\dots,x_n) \rightarrow K(j_1(k),j_2(k),\dots j_m(k)) \qquad (1)$$

where B(.) is a boolean function of binary variables x_i, and K(.) describes the states of the manipulator joints $j_1,j_2,\dots j_m$ which can be in one of the four states (k=1,2,3,4): rigid, loose, flexion, extension /4/. The motor function K(.) follows thus the pattern of joint states in the pain evasion reflex in the man. Evidently, the expression (1) can be easily represented in the computer knowledge base.

Although the expression (1) serves as machine representation of the simplest type of reflex response in the man, stimulating thinking about the nature of reflex control can be thus derived,

1. The type of reflexes in question are initiated by discrete changes of sensory signals. Such signals are highly insensitive to noise and errors.

2. Certain classes of proprioceptive and exteroceptive patterns associated with motor reflex actions are nothing else but combinations of simultaneous binary inputs. Consequently, the simplest type of learning at the reflex level consists of adding binary sensory stimulations to the existing pattern in a synchronised way. Formal description of such processes are logical and/or expressions.

3. Boolean expressions have the property that their solutions are independent of the number of variables. In other words, the response time of this kind of control in the man and the machine is independent of the complexity of the sensory input pattern.

4. The pattern matching control does not require any kind of mathematical structure in input and output sets. The one-to-one mapping between two sets belongs to fundamental operations of the set theory.

As seen, the formal description of monosynaptic, nonmodulated motor reflex leads to mathematical expressions of interesting nature. In order to be valid, these expressions do not require any kind of set structuring. Their implementation time is independent of the number of variables. The mapping operator corresponds to simple learning processes: memorisation of simultaneous discrete events.

The above lessons derived from the representation of the simplest reflexes in the machine are modest. But they are, certainly, improving our understanding of non-numerical control of this type. The reasons why reflexes are so essential for the survival of the biological world become highly transparent when they are represented in the machine. We have, therefore, full right to expect that further advances in reflex control of machines will help to improve our knowledge about the origines and the evolution of neuromuscular control.

Skill Control of Manipulation

The identification of the complex human automatic and reflex motions involved in grasping and manipulation in order to build intelligent robots is still at the beginning. Many factors make the grasping and the manipulation task relatively more difficult to reproduce in the machine than the locomotion function: increased number of degrees of freedom to control, richness of sensory feedback, complexity of patterns to recognise, etc. Nonetheless, the first attempts to develop skill based AI control systems for dextrous multifingered hands prove to be quite promising /6/. At this point, it is early to predict the long range impact of AI studies of reflex control in the man upon our understanding of neuromuscular activities, but some stimulating questions have been already raised.

From the knowledge engineering point of view, following issues related to target reaching and grasping in the man are of fundamental importance:

1. Anthropomorphic arm and hand are multivariable, redundant, mechanical system. In the everyday life, however, all men select automatically just a unique target approach trajectory and stable grasp out of very large number of options. By what constraints and optimisation criteria is the number of options being reduced to a single solution?

2. Automatic and reflex actions are, evidently, only efficient when applied to repetitive tasks. While this is so in many instances in locomotion, the case of grasping is quite opposite. In daily activities, we are hardly ever met with identical grasping tasks in terms of target shape, size, weight, position, texture, barriers to overcome, etc. What kind of neural mechanisms make feasible the use of automatic and reflex control for non-repetitive tasks?

3. As pointed out above, the redundant arm-hand extremity executes functional motions in a deterministic way. This is a surprising phenomenon in itself. But even more surprising is the fact that automatic (acquired) and reflex actions lead to the same target approach trajectory and the same stable grasping mode in all human beings regardless of age, sex, race, education, provided that task requirements are identical. Having this in mind, the question arises if it is possible to understand better by AI methods those common features of neuromuscular control which, in redundant systems, are producing the same functional response in all men for a given task?

At this stage of AI research in skill based expert systems, no definite answers to the above questions are available but some interesting hints have been offered. Let us start with the question number 1. In order to make the understanding easier, a simple, generic, grasping task will be analyzed. In Fig. 1a, the initial hand-target position is shown. For the sake of simplicity, both the hand and the target are laying initially at the table level. The unusual initial hand orientation at rest in Fig. 1a is taken by intention so that the alignment mechanism described in Fig. 2 can be better understood. The end position of the hand in the target approach phase is given in Fig. 1b. It was shown that the horizontal projection of the target approach trajectory in free space is a straight line /6/. Joint trajectories in human extremities are preferably without jerky movements which points out to the fact that energy saving criteria are essential in the execution of functional motions.

The target approach and preshaping process in the man, as shown above, appears to be trivial. But from the knowledge engineering point of view, interesting conclusions about invariant features of this motion can be reached. The first question to be asked in this respect relates to constraints which reduce the solution of the approach and grasping task to deterministic process. The constraints, acting at the automatic and the reflex level of this kind of functional motion, can be deduced from Fig. 2. Stated explicitly, they look as follows:

1. In the approach phase, the hand aims not at the proper center of the grasping zone C, but at point C' which is obtained by displacing C along the normal line. In this way, the hand is being prepared for safe grasping.

2. In the approach phase, the real grasping task is replaced by an equivalent abstract control process in which the hand is shrinked to a moving point to which alignment axes are attached. The ultimate goal of the hand orientation control in the approach phase is to align the corresponding hand and target axes. This is, as seen later, a necessary condition for safe grasp.

The combined effect of the above mentioned constraints:

- selection of smooth approach trajectory with straight line horizontal projection;
- reduction of threedimensional hand-target grasp to point-to-point tracking process in the approach phase;
- alignment requirement;
- decomposition of the arm function into propulsion and handorientation,

reduces the otherwise redundant biomechanical skeletal structure to deterministic motion. Let it be emphasized that the constrained functional motion as described above can be always realized by the means of automatic and reflex control since, at this phase of the grasping task, the details of target contour and of nonvisual sensory patterns do not affect the control.

3. We have now come to the crucial issue of the grasp control by automatic and reflex mechanisms. As known, grasping tasks in real life cover a very wide range of situations in terms of object sizes, shapes, weights, locations, etc. In order to apply reflex and skill based control, the enormous number of different grasping tasks must be somehow reduced to a small set of representative tasks. In this way, a relatively small knowledge base, combined with automatic and reflex control, should be able to handle efficiently the realities of life situations.

The knowledge engineering approach to the reduction of complexity of grasping tasks may be developed on the basis of following two postulates:

1. In the preparation for safe grasping during the approach process, the details of the target contour are not taken into consideration. For control purposes the real object is replaced by smooth circumscribed or inscribed, geometric primitive. The end point of the approach trajectory as well as the hand-target alignment are carried out with respect to the given grasping center of the geometric primitive. Consequently, the preshaping of the hand is determined by the shape of the geometric primitive rather than by details of the target contour.

2. Details of the target contour are taken care of by touch sensors. Once the hand contact with the object has been established, the shape adaptation reflex enters into the action which tends to maximise the available hand-object contact surface.

On the basis of the above assumptions, it is possible to design skill based AI control of manipulators with dextrous anthropomorphic hands. The knowledge base of such a controller consists of two important segments:

a) The set of representative grasping patterns for basic geometric primitives (less than 10).

b) The set of representative grasp modes of the human hand (less than 8).

As seen, the AI method designed to simplify the extreme diversity of grasping tasks leads to interesting solutions involving the transformation of actual visual information into simplified, general, abstract geometric forms and relations. Which of these mechanisms are functioning in the neural system, if any, remains to be explored by further multidisciplinary research. The point made here is that the above approach makes the great variety of grasping tasks amenable to reflex and skill based control in the machine. At any rate, the scene simplification mechanism is a prereouisite for automatic, fast, motor responses.

4. Safe, stable grasping implies that once the full contact of the hand with the object has been established, no relative motion should occur. This important feature of the human grasping action must be also incorporated in the machine. An obvious requirement for stable grasp is that the force produced by the thumb acts opposing to the direction of other finger forces. The AI approach, which reduces the above requirement to the level of reflex control, will be outlined below.

The human hand is, actually, a shape adaptive cover due to finger articulation and mobility. As pointed out before, the human hand preshapes during the target approach phase according to geometric primitives. In the grasping action proper, the hand adapts to details of the contour to be covered;

- the role of the alignment operation is to assure, within given coverage depth, the maximum contact surface between the hand and the object taking care that the force opposition requirement be satisfied.

Working now backwards, we realize that the reflex and skill based control of grasping can be derived from a heuristic optimisation criterion assuring high degree of safety and stability.

From the point of view of safety and stability of the grasp, the best solution taken from the allowed set of choices corresponds to maximum contact surface. In this way, the rationale of skill evolution involved in grasping may be interpreted in terms of a heuristic optimisation process.

Conclusion

Current research in reflex and skill based control of machines is illustrative if new attitudes to man-machine relations. Instead of thinking of analogies between the mechanical and the biological world, the field of knowledge engineering is being developed. In addition, complex, multidisciplinary efforts are initiated in order to bring closer basic research in brain studies, physiology, computer science. Evidently, the mechanisms of self-organised large systems are still far from being understood.

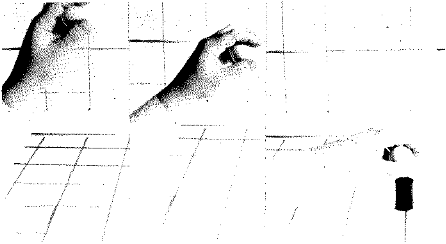
In the context of current AI studies, it is appropriate to ask the question of the transfer of motor skills and reflexes to the machine may help to understand better the lowest levels of selforganised motor responses and neural networks. In order to express our opinion on this matter, let us review briefly some results related to skill based AI systems which were outlined above:

- pattern-action matching control is the most general and fastest type of response which does not assume any kind of set structure or numerical data processing;

- skill and reflex control of manipulation tasks relies on smoothing and abstraction properties of vision systems. In this type of control, triggered by visual patterns, the details of sensory inputs are not involved, at least in the initial phase of motor response;

- the evolution of skill and reflex control from the multiple to the deterministic solutions is, like in any control problem, due to constraints and optimisation criteria. While the meaning of these optimisation criteria in certain instances may be guessed, it is hard to understand how selforganised systems generate, within themselves, their own complex optimisation goals and hierarchical control structures.

AI studies of transfer of skills to the machine will contribute, hopefully, to improved understanding of selforganised systems. The impact of such studies on rehabilitation engineering and restorative neurology is more imminent. Reflex controlled assistive systems are already in the phase of clinical evaluation. Hybrid assistive systems, combining internal and external reflex control, represent a new, promising trend in rehabilitation engineering. The possibility to inject external reflexes directly into the neural system is at our hands. The progress in knowledge engineering has reached such a level that the skill acquisition by the machine is now feasible. In other words, AI studies of skills and reflexes must be considered as an important tool in the development of neuroprostheses and restorative neurology as well.



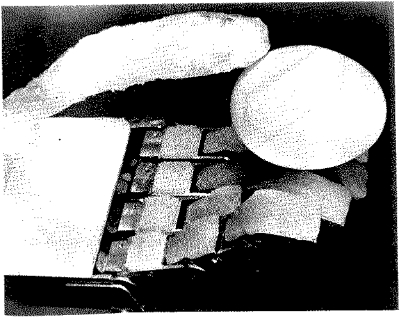


FIG1. HAND GRASPING

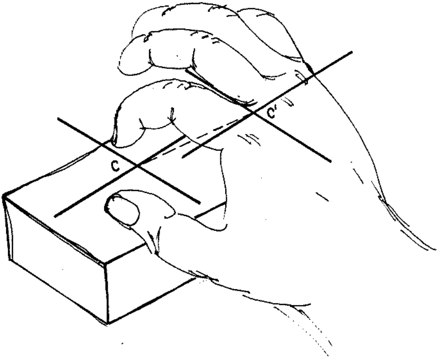


Fig 2. Abstract form of the real grasping task