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Computers, Brains, and the Control of Movement

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ABSTRACT. Many of the problems associated with the planning and execution of human arm trajectories are illuminated by planning and control strategies which have been developed for robotic manipulators. This comparison may provide explanations for the predominance of straight line trajectories in human reaching and pointing movements, the role of feedback during arm movement, as well as plausible compensatory mechanisms for arm dynamics.

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Robotics and biological motor control can progress more readily by a sharing of ideas between the two fields. For example, many of the problems associated with the planning and execution of human arm trajectories are illuminated by planning and control strategies which have been developed for robotic manipulators. This comparison may provide explanations for the predominance of straight line trajectories in human reaching and pointing movements, the role of feedback during arm movement, as well as plausible compensatory mechanisms for arm dynamics.

The application of principles of robot arm control to biological arm movement control rests on the premise that at a certain level of abstraction, since the problems are common to both the artificial and the biological systems, the solutions will be too. For example, both systems are required to propel linked masses in a gravity field to achieve a goal, such as grasping or throwing an object. In addition, while producing such an arm trajectory each system must satisfy the mechanical constraints imposed by joint geometry. The solution must also satisfy the physical constraints imposed by tasks such as opening a door or sliding a drawer. To be sure, at some point the trajectory plan must be transformed into signals appropriate for motors or muscles, but these differences should not obscure underlying similarity imposed by natural constraints.

Considerable progress has been made in the past 15 years in understanding control of robot arm movement for several reasons. Abstract consideration of problems encountered in achieving a trajectory has led to theoretical insights which can be translated into general control strategies. Moreover, attempting to program a computer to control a robot arm forces one to face squarely every difficulty and hidden assumption. Lastly, it is possible to test a control strategy in a way not possible with biological organisms. Out of this work has emerged a conceptual structure for the general planning and control of movement. This conceptual structure and resultant hypotheses for biological motor control will now be discussed.

Object level planning

A hierarchical movement plan is developed at three levels of abstraction (Figure 1). The top level is the object level, where a task command such as pick up the cup is converted into a planned trajectory for the hand or for the object held by the hand. At the joint level the object trajectory is converted to coordinated control of the multiple joints of the human or robotic arm. At the actuator level the joint

Figure 1. A three-level hierarchical movement plan which converts a movement command to muscle activations by first planning the movement at the object level, then translating the object trajectory into coordinated joint movement, and finally converting from joint movement to muscle activations.

movements are converted to appropriate motor or muscle activations.

The first hypothesis is that movement is planned at the object level rather than at the joint or muscle level. Our hands are the usual instrument for manipulating the environment, and the rest of the arm can be viewed merely as the physical means by which the hand can be moved. In robotics, straight line movements of the hand are preferred for reasons of planning collision avoidance, of minimizing distance of travel of the grasped object, and of minimizing inertial forces on the object (important for avoiding spilling a cup of coffee).

The preferred trajectories for human or primate arm movements are also straight lines with the hand[8,12]. On the surface this result is puzzling because of the complicated relation between joint positions and hand positions, so that the joint movement to support a straight line hand movement is complex. One might suppose that the human motor system would choose simple joint movement strategies for ease of planning and control, in which case the hand movement would be complex. Researchers have sought biomechanical rationales for these observations. Yet straight line movements minimize neither energy consumption nor time of flight as determined by solving the corresponding optimal control problem. Furthermore neither the presence of muscles which extend over more than one joint nor the spring-like properties of the muscles themselves favor straight line movements over other movements.

The mystery disappears if one accepts the hypothesis that movements are planned at the object level. The acceptance of the object level hypothesis places severe requirements on the motor system, which must

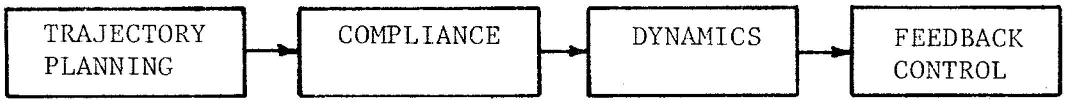

Figure 2. A modular structure for a control system involving a trajectory planning module to obtain a time sequence of positions, a compliance module to synthesize a force control strategy when there are movement constraints, a dynamics module which involves torque production to realize planned positions and forces, and a feedback module which corrects deviations from these plans based on sensor readings.

now translate hand or object trajectories into a complicated joint movement and thence into actuation of the joint musculature. This is not to say that properties of the biological system such as muscle characteristics, sensing accuracies, nerve delays, and processing capabilities do not influence the choice of hand trajectory. Rather, biological properties are viewed as offering broad constraints, but within these constraints movement planning occurs at the object level without any need for detailed consideration of these properties.

The Modularity Hypothesis

In robotics the requirements on a control system to realize a planned object movement have been extensively investigated, and a modular structure for planning and control has emerged (Figure 2). In the trajectory planning module the spatial and temporal aspects of positions during a movement are developed. In the compliance module environmental constraints such as opening a door are synthesized into combined force and position control. In the dynamics module the torques required to realize planned trajectories are found. Lastly, in the feedback control module corrections to executed trajectories based on desired planned movements and trajectory errors are determined from sensor readings.

These four planning and control modules can be developed at each of the three hierarchical levels listed above, with the module content varying with level. Whether a module is developed at a particular level varies with the particular robot system implementation. For example, some robot systems plan trajectories at the object level only at the movement beginning and end and plan all intermediate points at the joint level. Some robot systems make feedback corrections based on errors at the hand, while other systems make feedback corrections either at the joints or at the actuators. This conceptual structure is an intersection of two separate structures, and therefore differs from the strict hierarchical sensorimotor representation of Saltzmann[11].

The modularity hypothesis is that the biological planning and control process is structured into these four distinct modules at some level. Analogously, in biological vision the lower level vision processes are divided into such separable modules as filtering, edge detection, binocular stereo, and surface interpolation. The advantages of a modular representation over more amorphous representations include perspicuity and evolutionary constructibility. In fact a stronger hypothesis may be proposed, namely that if a control system is not structured in this manner, then it will not have a general movement control capability. There must exist classes of movements which the system cannot achieve, or there must be limitations in adaptibility. Examples of limited control strategies are final position control[2], where there is no explicit trajectory control or joint torque computation, and optimal control, where mathematical complexity forces precomputation and tabularization of solutions.

If the biological motor control system does not have a general control capability, then a research strategy for studying the system is to attempt to categorize precisely which movements can or cannot be achieved. A major difficulty in this attempt has been the measurement of unrestrained three-dimensional movement, which however new apparatuses such as the Selspot System are making more feasible. Specific predictions about appropriate experiments can be made by examining possible implementations of the modules, including simplifications and combinations of modules. Another research strategy is to presume that the biological motor control system has found simplifications or shortcuts which generate near-general behavior. In this view the movements that the motor control system can produce are good enough for the vast majority of circumstances. One can then examine requirements for basic movement tasks, and attempt to deduce simple control strategies which are adequate for the tasks.

In the remainder of the paper the modularity hypothesis is pursued by examining algorithms and requirements for strategies developed in each module. The relevant robotics research will be used either to suggest possible mechanisms for control of biological free arm movement or to shed insight into the nature

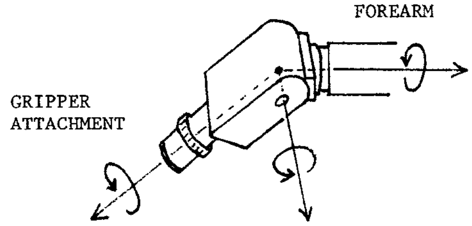

Figure 3. A typical robot wrist assembly with three consecutive rotary joints whose axes intersect at a single point. There is a twist movement between the forearm and wrist assembly, then a flexion movement in the middle of the wrist, followed by a twist movement at the wrist end.

of the problems involved.

Trajectory planning

One of the problems in trajectory planning illuminated by robotics research is the computation of joint angles from hand positions. It must be possible to make this computation rapidly in order for the control system to plan movements at the object level. It is known that the joint-angle computation for an arbitrary linkage mechanism must ordinarily proceed numerically rather than analytically, yet numerical computations are too time consuming for object level planning. Fortunately time-efficient analytical computations exist under certain conditions. One such condition is the intersection of the axes of rotation of the last three degrees of freedom at a common point, which is to say that the hand is connected to a three degree of freedom wrist. The three orientation parameters of the hand can be computed separately from the three position paramers[9], because the three wrist angles are easily found from the hand orientation and the remaining linkage angles are set to attach the wrist end. Nearly all robotic manipulators are designed to satisfy this condition, usually with a twist movement between the forearm and wrist assembly, then a rotary joint in the middle of the wrist, and finally a twist movement at the end of the wrist at which the grippers are attached (Figure 3).

The human arm meets this condition as well, but with a different kinematic arrangement. The wrist has two degrees of freedom, abduction/adduction and flexion/extension, while the wrist supination/pronation is supplied by forearm twist. Therefore the human arm has at least in principle the right structure to allow object level planning of movement. The human arm actually has seven degrees of freedom (three wrist, one elbow, and three shoulder joint freedoms), which is one more degree of freedom than the six needed for general positioning. The redundant degree of freedom is useful among other things in obstacle avoidance, for example holding the elbow up to avoid bumping into a table when reaching for a cup.

Compliance

Much of the current work on biological motor control has been concerned with processes involved in the trajectory formation of free arm movements, as opposed to contact movements associated with the interpretation of touch information, the control of force and compliance, and dexterous grasping of objects. Contact movements complicate the control problem considerably, and so it is appropriate that physiologists have concerned themselves first with the simpler problem of free arm movements. Compliance is one of the most pervasive and difficult aspects of control from a robotics standpoint, often for sensor instrumentation reasons, and it may be hypothesized that much of the biological motor apparatus is concerned with the control of compliance rather than with the control of free movements.

Although the control of compliance is reasonably well understood in robotics, this area of research is undeveloped in biological systems. One can expect that when physiologists eventually turn their attention to the control of contact movements the relevant robotics research will apply as well. Conversely, biophysical research of touch sensing will aid the development of this aspect in robotics, just as the study of human vision has aided the development of computer vision[7].

Inverse dynamics

For two joint planar human arm movements, joint angle computations are simple because only the shoulder and elbow are involved. Their conversion to joint torques, not usually considered by physiologists when studying arm movements, is however not so simple. The problem is that the forces and torques experienced at one link are reflected to other links as well. Those link interaction forces and torques proportional to joint accelerations are termed *inertial forces*, those proportional to the product of two different joint velocities are termed *Coriolis forces*, and those proportional to the square of a joint velocity are termed *centripetal forces.* In addition there are non-interaction forces and torques due to gravity and to the viscosity and elasticity of tissue. The inertial forces are the normal action-reaction forces experienced when accelerating a body, the Coriolis forces are similar in nature to the forces causing whirlpools, and the centripetal forces are like those acting on an object attached to a string and whirled in a circular orbit.

Much work has been done by motor physiologists on single joint movement, such as elbow flexion or head rotation. While some valuable results have come out of this research, it is clear that control strategies for single joint movement do not necessarily apply to multiple joint movement. For example, interaction forces are nonexistent in single joint movement, but they cannot be ignored in multiple joint movement. This means that applying control strategies for single joint movement to multiple joint movement will result in errant trajectories.

Both the effects of simplifying the dynamics computation and the limitations of feedback control in biological arms (discussed shortly) strongly suggest that there must exist substantially correct preprograms in order for humans to make accurate fast arm movements. Experimentally, the importance of preprogramming in the control of movement has been well established[2]. The conclusion is that the motor system must do a very accurate job of solving the inverse dynamics if it is to execute successful arm movements.

Fortunately methods for efficient computation have received thorough study and development in robotics, so do these methods suggest possible mechanisms for biological dynamics compensation? Analytic solutions based either on recursive Newton-Euler formulations[6] or on recursive Lagrangian formulations[4] offer fast, general computation of the joint torques. Starting from a planned trajectory expressed as a time sequence of joint angles, the recursive solutions work by calculating the angular and linear velocity and acceleration vectors from the joint angles and their rates working from the base of the manipulator to the hand, then recursing backwards from the hand to the base calculating the forces and torques. Tabular solutions, originally proposed as plausible biological mechanisms[1,10], trade off memory for computation by precomputing portions of the dynamic equations. These tabular solutions are not as general or accurate as the analytic solutions due firstly to the need to quantize continuous variables to fit into discrete memory, and secondly to the inability to adapt readily to mechanical changes such as when picking up an object because the masses and inertias are inextricably bound in a table.

The current state of our understanding of human dynamics compensation has not developed far past the point of enumerating the possibilities and of carrying through the consequences of a particular proposed mechanism. For example, the consequences of a tabular based system would be that learned movements are not generalized well to other movements and that adaptation to mechanical changes would be very slow. Human motor performance is ambivalent on this point, with some tasks such as throwing objects of different sizes and weights readily learned and others such as playing tennis or golf learned only with great difficulty and expenditure of time.

Are there any classes of trajectories for which the dynamics computations are particularly simple? In the course of our research we have identified a strategy making it very simple to scale the speed of movement[5]. When changing the speed of a movement, for example going faster in one part and slower in another, normally the inverse dynamics must be recomputed from scratch. However, in the circumstance where the shape of the velocity profile along the path is simply scaled in time, it is possible to avoid a complete recomputation of the dynamics. If the velocity profile is scaled by a factor r, then simply by scaling the time dependent portion of the torque program by a factor r^2 and then adding in the gravity contribution without amplitude change the same path will be followed but at the new speed. One might conceive of a practice strategy beginning with slow movements to learn the basic torque profiles, then simply scaling these profiles to increase the speed of movement.

Measurements of human arm movements between two targets at different speeds seem to indicate that human subjects follow this strategy approximately [Figure 4]. The net torques at the shoulder and elbow joints acting during the trajectory were inferred from the dynamic equations and the measured angles and their time derivatives. The fast movement in Figure 4 was roughly 0.5 seconds in duration, the slow movement approximately 1 second. In this plot, the shoulder and elbow torques of the slow movement were scaled to match the peak torques for the fast movement, and the square root of the scale factor was applied to compress the time axis. The profiles are seen to overlap substantially.

Feedback

In robotics there is nearly instantaneous, accurate feedback of position and velocity at the joints of the manipulator. Disturbances to the movement or errors due to modelling inadequacies can be overcome by feedback. For example, as has already been mentioned it is possible to apply single joint strategies to

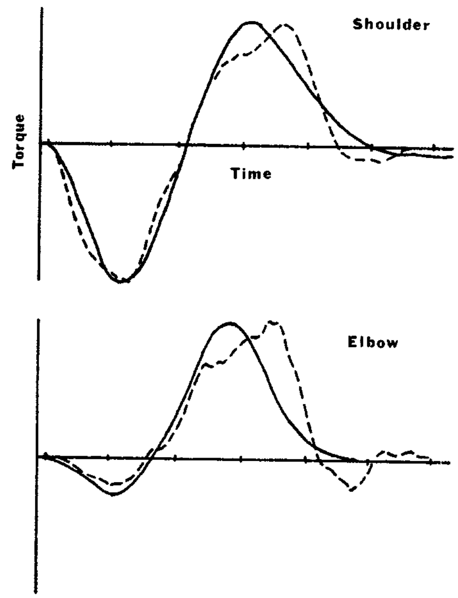

Figure 4. Torque versus time curves for two arm movements between the same targets but at different speeds: the solid line represents a 0.5 second movement, the dashed line a 1.0 second movement.

multiple joint movements provided interaction terms are ignored. But as the speed of movement increases the interaction terms become more important. Unfortunately this imposes severe demands on the feedback controller, with the end result that it will finally become unstable. Thus inadequacies in the inverse dynamics ultimately limit the safe speed at which a manipulator can be moved.

For biological arms, limitations in the feedback system impose even more severe demands on the control system. Signals from proprioceptors seem subject to many different conditions, so that their accuracy and fidelity as monitors of joint motion is far from clear. There are substantial delays in the feedback loop as well; for example, the supraspinal loop requires 70-100 milliseconds. While the spinal loop is faster, experimental results indicate that the contribution of the spinal loop to load compensation is insubstantial[2]. Feedback delays also limit controllable speeds of motions. If the system is changing rapidly, then by the time a feedback signal has been used to modify the motor commands the system will have evolved to a new state for which the corrective signal is inappropriate. For fast arm movements in the range of 500-600 milliseconds the supraspinal loop delay is too long to serve the role of a feedback controller.

Because of the difference in feedback between biological and robotic arms, not all robot control strategies are acceptable biological models. Recently a strategy involving measurement of hand acceleration was proposed as a biological model[3], unfortunately without considering whether there is any way that the biological system could make this measurement. Even for robotics this strategy has never been implemented because of the instrumentation problem for hand acceleration measurement (noise, sensitivity, durability, etc.).

Conclusion

Robotics is a new field, and its impact on our thinking about biological motor control processes has just started. Actual successful applications of robotic concepts to biological systems are likely to evolve gradually because of inherent difficulties of testing and evaluation in studying motor control. Nevertheless robotics does provide an infusion of new ideas into this very difficult field.

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