Human Sensori-Motor Development and Artificial Systems

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Abstract

The aim of this paper is to illustrate some of the peculiarities of human sensori-motor development for the execution of visually guided reaching and to suggest a similar framework for the implementations of artificial systems able to adapt to changes in sensory and biomechanical constraints. In particular the problem of mapping sensory information into direct motor commands will be presented and the advantages of a closer synergy between the study of artificial systems and neurosciences will be discussed [20].

1 Introduction

The main objective of this paper is to present a framework for the design and realization of artificial, adaptable, intelligent systems. Our assumptions are the following:

1. the systems have to work and cooperate with humans;

2. the problems to be solved cannot be fully predicted.

Given these assumptions autonomous systems have to incorporate anthropomorphic features at the sensory, motor and cognitive levels. Sensory anthropomorphism is motivated by the fact that having to work with humans, artificial systems have to perceive the environment at least as humans do in order to be able to receive all direct and indirect messages through their sensory channels (being it speech or alarm signals). Motor anthropomorphism is required if the artificial system has to work in environments and with tools specifically developed for humans. For example must be capable of navigating through stairs or handle a hammer or a wrench (this is particularly true for systems specifically designed for maintenance where electric power to operate elevators and electrical tools may not be available). In both sensory and motor perspective, anthropomorphism has to be taken from the functional perspective and not necessarily from the morphological one. If it is possible to design a "locomotion device" which can support navigation in flat as well as irregular grounds, the overcoming of small holes or obstacles etc., it is not strictly necessary to think of "legs". On the other hand, if "legs" are a reasonable solution they should not be discarded just because "cars have wheels" or airplanes do not flap their wings. We can state quite confidently that there is, at present, no vehicle moving on ground that has the level of mobility allowed by legged locomotion. Certainly controlling two (or four) legs is more complicated than controlling two (or four) wheels but, with the assumptions made at the beginning, we may not have alternative solutions.

The second assumption is, possibly, even more relevant. It is now clear to most of the people working with robots that it is impossible to predict all possible events (even in partially constrained environments) and, consequently, artificial systems with fully predictable behaviors are no more realistic than humans with totally predictable behaviors. On the other hand it is possible that designing an adaptive system with a level of adaptability close to the one shown by humans, is far too complicated not because of the complexity of the resulting system but because of the impossibility of predicting (and pre-coding) the variety of interactions occurring between sensory, motor and cognitive processes required by adaptive behaviors.

Considering the biological analogy it would be like expecting nature to "engineer" a newborn with the kind of skills and adaptability shown by adult humans. The amount of "coding" required would be far too much even with respect to the enormous amount of information genetically coded in a newborn.

Experience plays a fundamental role in shaping human behaviors and in achieving the level of adaptability we would like artificial systems to show. The main point we would like to make here is that adaptability cannot be engineered but must be acquired through a slow, experience driven, process. The proposal we make is to use human development as a model to design and build adaptable systems. In the remainder of this paper, we will focus on early sensori-motor development in human infants during the first postnatal year.

The study of sensori-motor coordination in artificial systems has been carried out mainly by analyzing and trying to implement skill levels comparable to those of adult humans. For example the control of robot's heads as well as visually guided manipulation tasks have been studied with reference to psychophysical data measuring the performance of adult humans and animals. In spite of the recent advances in this area, the systems implemented are still far from achieving human-like performance levels and task flexibility. In our view, this difficulty arises, from the traditionally implemented approach of constructing a complex system: to make the problem more tractable, sensori-motor coordination is broken down into a set of sub-problems often defined by a specific sensory modality (e.g. vision, audition, touch etc.) or specific motor skills (e.g. manipulation, gaze control, navigation).

A different solution is used in humans and other animals, where adult-level performance is achieved through the simultaneous development of sensory, motor and cognitive abilities. This process is not simply caused by the maturation of the single components or the learning of progressively more sophisticated skills. Instead it is marked, particularly in the very early stages, by a sequence of changes of the neural circuitry, by a strategic exploitation of the environment with a limited set skills present at each developmental stage, and the ability of biological systems to calibrate themselves in the presence of ongoing environmental and anthropometric changes. Very recently a few research groups around the world (e.g. [5, 3]) have started exploiting the "developmental" analogy to investigate if, by adopting a similar methodology for artificial systems, better insight on how to build highly complex systems and how to better understand brain functions can be derived.

In order to explain the significant difference of the developmental approach some highlights of human development is presented and the issues relevant to the study of artificial development is outlined with particular emphasis on visually guided reaching.

2 Human Development

It is outside the scope of this paper to present an in depth description of human development. For this reason a brief outline of the main research results will be presented with particular emphasis on the early stages of development namely from birth to about 12 months and with particular reference to the onset of sensory-motor coordination [22] and and visually guided reaching.

Piaget's naturalistic observations have served for many years as a landmark in the study of grasping gesture. For Piaget sensory messages are rather unstructured at birth and are exploited by the developing system to transform neonatal reflexes into independent action schemes. For example impulsive arm movements and the grasping reflex, when used repetitively, becomes prehension schemes. In Piaget's view, the fields of touch and vision are initially separated and autonomous as if the eyes and the hand operate on different spaces. The action schemes (such as grasping) are necessary to establish the link between the two domains. *The sight of the hand is a necessary stage in prehension-vision coordination*

> at a given moment, infants grasp the object when they see them in the same visual field as their hands, and then look alternatively at their hands and at the objects [19]

The simultaneous exploitation of vision, touch and motor schemes establishes the link between multimodal sensory experience and motor act.

2.1 From birth to the onset of goal-directed reaching

Two tasks of coordination are required to perform successful reaching. First, any neural controller must be capable to interact with its *plant* (i.e., the arm in this example) in such a way that centrally planned, complex actions can be executed. Second, visually specified goals must be linked to appropriate motor acts. These motor acts, in turn, must be suitable to move the arm to the desired goal. At birth human infants are not equipped to solve these two tasks:

- They have limited postural control of the trunk, head and arms. Appropriate head and trunk righting reactions begin to emerge 2-3 month after birth [16].
- They have limited knowledge about the physical makeup of their bodies (i.e. moments of inertia, viscosity, stiffness). By performing undirected, spontaneous movements they are able to *experience* the physical world and calibrate their motor system appropriately. Without this calibration no goal-directed action could be performed successfully.
- They have a limited movement repertoire consisting of an array of infant reflexes (i.e., grasping, sucking), and basal intra- and interlimb synergies (coupled flexor, extensor activity, co-activation) [2, 11].
- They have limited visual capabilities. During the 1st postnatal month, the visual system provides the infant with functionally useful, but unrefined vision at a level of approximate 5% of adult acuity level (20/800 on the Snellen scale). The infant can likely differentiate facial features from a distance of about 50 cm. Objects beyond this distance are probably not seen clearly [1].
- They have not established a finite neural control structure. Most cortico-spinal projections are not differentiated. In a first stage, cortical neurons from all areas of the neocortex send collaterals to subcortical structures - a process termed arborization. In a second stage, these collaterals are pruned according to their later function (i.e., a visual projection, or motor projection) (for a review, see [18]).

Human infants attempt their first goal-directed reaches around the age of 4 to 5 months after birth [26, 13, 23]. Before this time, human infants will not reach consistently for objects in their immediate surround. However, a few days after birth infants are clearly capable to perform anticipatory arm movements when trying to intercept a moving target [25]. It is believed that such interceptive actions are triggered by the presence of an object in the field of view. The movements themselves do not resemble coordinated reaches. They are either short swiping motions or relatively long lasting jerky movements. They look like pre-programmed, ballistic motions resembling reflexive actions (for example trajectory correction is absent and the transport and approach phase are not separable) [4]. At this developmental phase the role of visual information is more that of initiating the movement of the arm in a *reflex like* fashion. The link between vision and motion present at birth seems to be limited to the side, and roughly, the position of the object in the field of view. The hand is kept with the palm open (possibly to maximize the probability of making contact with the object) and the role of visual feedback (and particularly of foveal vision) seems to be irrelevant [21].

2.2 Development of goal-directed reaching

As mentioned above, the first goal-directed reaching movements are usually seen between the 4th and 5th postnatal month (the so-called *gross-motor reaching*). The emergence of goal-directed behavior at this time is not coincidental:

By that time infants had enough time to calibrate their sensory as well as their motor subsystems. Visual acuity has improved considerably and is now in the range of 20/200. Around two-thirds of the infants at that age have obtained stereoscopic vision, thus are capable of using a powerful cue of depth perception. Higher motor centers are operational and reflex behavior can effectively be inhibited to enable the system to acquire more flexible, task-oriented motor behaviors (i.e, suppression of the grasp reflex or the asymmetric tonic neck reflex)

When young infants attempt their first reaches, their movements are jerky and look ataxic. In contrast to the stereotypic kinematic patterns seen in adults, infants' hand paths do not follow a straight line, nor do the corresponding velocity profiles reveal a bell-shaped form [24, 13, 15]. Within the first 4 to 8 weeks after the onset of reaching kinematic improvements are dramatic. At the onset of reaching, their hand trajectories consist of about 5 segments. Two months later, the number of movement units of the hand is halved. By the age of 7 months, a typical reach consists of one large transport segment and one or two additional units in the approach phase. During the approach phase the palm is usually kept open - a precision or pinch grip has not yet developed. In this first phase of gross-motor reaching, infants need to learn to time their neural impulses in such a way that the hand does not over- or undershoot the desired object. In order to achieve this goal, they have to embed basal muscular synergies that are present at birth (i.e, flexing the elbow), into functional, task-adequate multi-joint movements. That is, during early reaching emphasis is put on refining the transport phase, not the approach, nor on skillful handling of the grasped object.

In a second phase (*fine-motor reaching*), beginning about 3 months after reaching onset, infants work on *fine-tuning the system*. By now they reach consistently for objects in their surround. Missing the target is no longer observed. Instead, infants will improve on their manipulative skills (i.e., precision grip). Next to these advancements in the approach phase of the reach, infant motor systems continue to refine the transport phase. Kinematically, their hand paths become straighter, but more important, they learn to exploit external forces for their movement goal. For example, they learn that gravity and motion-dependent forces alone can extend their forearms. Consequently, they do not have to initiate elbow extension through muscular activation, but let gravity do the work [12]. As a consequence of this learning process, infant movements become more economical - muscles will only be activated when needed. However, an adult-like skill economy will not develop before 24-36 months of age [14].

Within the first year of life, infants also develop the ability to detour around a barrier to retrieve objects. That is, not only the pure motor act is acquired, but also its adaptive use. This adaptive behavior was demonstrated in the studies by Diamond [6]. Using a small transparent box with one face open, they studied how infants reached for a toy inside the box (the toy is always visible but can be reached only through the open side of the box). 7-months-old infants reach for the object only through the same side of the box through which they see the toy. The reaching trajectory follows the line of sight. Successful reaching is achieved only if the object is seen directly (i.e. not through one of the transparent side). At about 8-9 months of age, a separation of the line of sight from the line of reach may be observed: infants can look through one side of the box while reaching through another. However, at this age they still need to see the toy through the opening on each trial in order to succeed (the memory of having seen the object through the opening is enough). By 11-12 months of age infants become perfect on the object retrieval task being able to reach the toy from any side of the box efficiently.

3 Relevant Issues for Artificial Development

In relation to what has been presented previously, the aim of this paragraph is to highlight the peculiarities of human development that, in our view, may be relevant to the design and implementation of an artificially developing system.

3.1 Development of an integrated system

The first and major observation relates to the fact that the newborn, in a systemic way, is a "complete" system in the sense that most sensory and motor components are present and functional. Each component may not be fully developed, but the available degree of interaction between sensory and motor systems allows for the emergence of sensory-triggered or sensory-guided motor behavior.

Sensory-guided coordination is absent at birth but other mechanisms, such as motor reflexes and sensory-triggered motion, are present exploiting the still limited sensory and motor abilities and allowing the infant to start some form of interaction with the external environment and the acquisition of the first sensory-motor experiences.

Throughout the developmental stages described previously, the maturation of all "sub-systems" proceeds harmonically and motor performance is matched to sensory and cognitive abilities. It is worth noting, however, that this process cannot be modeled entirely as a "learning process" because, during the development, the system itself changes its own motor strategies drastically. For example from a purely reflexive system to a system capable of voluntarily initiating "dominant motor sequences", arriving finally to complete voluntary, sensory-guided control.

During these phases, some of the abilities are only temporarily present (for example, some of the early reflexes) and are strategically used to take full advantage of the skills present. After a few months, these reflexes begin to "disappear", that is, they can no longer be triggered by a specific sensory stimulus (We will see later that the underlying muscular synergies remain intact). For example, the infant does not "learn" to control simultaneously all the degrees of freedom of his/her arms, but the first exhibit of reaching behavior is a ballistic-like, posture-dependent (e.g. through the tonic neck reflex) swiping motions of the arm with no ability to correct the trajectory nor to control pre-grasping postures of the hand. In some sense the system seems to practice with just a few joints before attempting more complex motor acts. The underlying control structure takes care of maintaining archetypal postures, controlling in a reflexive way the remaining degrees of freedom (e.g. by maintaining fixed angles at the joints at the elbow and wrist).

Reflexes, such as the grasping reflex and the tonic neck reflex, are present to facilitate the interaction with the outside world, even with such a limited control strategy, in order to provide a sufficiently high success rate. In this respect, one could argue that, if all degrees of freedom were under voluntary control, it would be a lot more difficult (and may be even impossible) to learn complex motor actions. The fact that the infant is not motorically and perceptually skilled becomes, in this view, a positive factor because it makes "successes" more probable and easier to repeat. This is true, of course, if the system is "designed" in such a way that the motor, perceptual and cognitive abilities proceed harmonically.

Some of the Piagean stages actually describe the behavior of *a different system*, in the sense that the control strategies adopted by the newborn and a 9 month old baby are radically different. This "developmental approach" differs substantially from a traditional "learning approach" because a learning system uses its own successes and errors to modify the parameters of an unchanging control system while development involves "structural changes".

3.2 One's body as external environment

Another issue worth stressing is the role of the infant's own body in development. It is universally accepted that development is very much dependent on the ability to interact with the external world. Yet newborns do not have much control of their own body and are virtually incapable of effectively controlling the external environment. Even the newborn's own body can be seen, from a control point of view, as a part of the "external environment" in the sense that it is not controllable (or the infant may still not be aware of the fact that it is "under voluntary control").

The newborn does not discriminate between a moving object and the motion generated by his/her own body (e.g. the "swiping hand" or the apparent motion induced by the motion of the head). As a matter of fact, the appearance of the newborn's own hand in the field of view produces an attention shift as in the presence of other "unexpected" events. ¿From a developmental point of view we could say that the first important sensory-motor experiences of a newborn are, indeed, stimulated by the newborn's own body. The body becomes an essential tool to establish and exercise the coupling between perception and action and to synchronize their development. Self-generated perceptual experiences have the double value of exercising motor and perceptual skills as well as their coupling. The fact that self-generated motor commands elicit specific sensory feedback (like proprioceptive signals, motion in the visual field, tactile stimuli or sounds) not only give the newborn a motivation to repeat (or not) the command (in order to repeat the sensory experience), but also are a powerful tool to adjust and refine the motor command "at will". As a result, the infant becomes aware of his/her own body and, consequently, becomes aware of the existence of an "external environment". The distinction between what is controllable and what is not is, in many senses, the first achievement of a system whose survival depends largely on its interaction with the outside world.

3.3 Role of inhibition

The final remark we would like to make is related to a major mechanism used by nature, through the early development of sensory-motor coordination abilities. Let us present it as a paradox: development progresses not by "learning how to do things that are unknown" but by "learning how NOT TO DO things that are known". The first observation is that a newborn is not "totally" incapable of doing things but is born with some basic motor skills (mainly reflexes). For example the already cited grasping reflex causes the newborn to close the hand as soon as the palm is touched. We have already discussed the role of this reflex in giving the newborn a way of starting to interact with the world even if the fine control of the hand's muscle is still outside his motor abilities. What is even more surprising, in this context, is the fact that this reflex disappears after a few months. What is the "motivation" for this? Certainly the fact that, as soon as the infant becomes potentially able to control his hand's motion, the grasping reflex is no more an advantage but becomes an obstacle to voluntarily exercise this ability (which, by the way, is essential for the survival of animals with prehensible hands) and to experiment with more complex interactions with the environment. Consequently, the key control issue becomes, that of **inhibiting** something that has been, up to that moment, a very useful and powerful tool. However, in this context it is important to note that the **inhibition** of a reflex does not imply that the underlying muscular synergies are wiped out or supressed by the activity of higher cortical centers. These synergies are still present and will be embedded into voluntary action. What is inhibited is the link between a specific sensory stimulus (i.e., touching the infant's palm) and a distinct motor respons (i.e., the grasping gesture).

The relevance of inhibition is not limited to these very early stages of development. Later, the infant passes through phases where the complex motor patterns acquired though a repetitive presentation of the same stimulus (such as the ability to reach with the hand objects repetitively presented in the left side of the field of view) are erroneously elicited in the presence of similar stimuli (e.g. if the object is presented in the right side of the field of view the reaching is still addressed, erroneously, to the left side). In other words, the development of complex sensory-motor skills by repetitive execution of the same behavior is followed by the development of the ability to "inhibit" such behavior whenever inappropriate. It is as if all newly acquired skills becomes predominant behaviors (possibly because, in order to acquire them, they have been repeated more often than others) which are used like reflexes. The successive stage is that of learning when to inhibit them.

4 Artificial Development (developmental engineering)

At the light of what has been presented so far, development is described best as an **evolutionary** process more than a **learning** one. Sensory, motor, and cognitive capabilities evolve and are adaptively exploited to interact with the external environment. The main difference between evolution and development is that, while evolution is mainly driven by "chance", development is, in some way, "built-in" and its "final goal" is more or less bounded by the structure and performance of the human body. Engineering a developmental process means, in this respect, being able to define a sequence of events causing the system to become incrementally more skilled. The big question here is who (or what) drives the incremental process and the main engineering problem is how to design it.

One way of looking at it is to see the goal of development that of being able to control a huge number and variety of "signals" and development as a dynamic process, incrementally selecting, among all possible control variables, those that match the current skills. The parameters which are not voluntarily controllable are driven by the system as "reflexes". Within this schema, designing a developing systems means to define the sequences of actions that, on the basis of acquired skills, set the successive goals of the system. Two aspects are, therefore, crucial: i) the starting point and ii) the development "rules".

First we need to define in a reasonable and feasible way the "artificial infant' or, in other words, what is the minimum set of functions that need to be present in an artificial system to be considered a meaningful model of a newborn. Secondly the dynamics of the development process need to be defined.

4.1 The artificial "newborn"

Within this developmental approach, work has been initiated to try to define a suitable computational framework for artificial development. The first practical problem is to define the subset of sensory and motor skills that should form the basis of the *artificial newborn*. The key issue, in fact, is to study and implement a "complete" system. In practice, this relates to the question of how many sensory modalities and how many motor degrees of freedom should be allowed at system "birth". The second problem is to define a computational framework for sensori-motor coordination which can support the kind of developmental adaptability described above.

As to the definition of the "artificial newborn" the closest (and possibly the simplest) approximation is a *humanoid system* composed of a stereoscopic head and a arm. This structure allows the coordination of vision, proprioception and touch/force with head, eye and arm movements to be studied in relation to development of goal-directed reaching. This system (we named it *babybot*) is currently composed of a 5 dof head controlling two retina-like cameras and a 6 dof arm with a force/torque sensor at the wrist.

As to the definition of the computational framework for sensori-motor coordination the major requirements that have to be satisfied are two:

1. sensori-motor coordination must be adaptable so that, for example, changes in biomechanics and sensory input can be "corrected" by the

system. The equivalence with human development here is adaptation to changes in size and weight of various arm segments, the adaptation to kinematic changes of the eye-head-arm system, and the increase in sensory accuracy.

2. the motor control structure should be based on motor primitives that can evolve from a purely reflexive behavior into a voluntary control scheme.

The approach we decided to follow derives from investigations on the spinal cord [7, 17] that has shown how movements of the limbs can be generated by combining simple motor primitives that can be modelled as force fields corresponding to the activation of a synergy of muscles. The action produced by the simultaneous activation of a set of motor units can be represented by a total force field which is a combination of the primitive's force fields.

In the cases where the field is convergent, its 'equilibrium point' (EP), can be thought of as the point toward which the end-effector is moving at each instant of time. The sequence of positions of the EP respect to time is often termed virtual trajectory. Even if the assumption that motion planning can be accomplished just by programming the virtual trajectory has been questioned recently [9], the EP scheme potentially maintains some advantages, like the reduction of the amount of redundancy and the simplified motor commands generation.

Moreover, the relatively small number of motor primitives required, could be thought of as being the basis functions of the "newborn" with the advantage that the system is capable of performing coordinated arm motion since its birth. More complex motions, and/or adaptation to variable external forces, are obtained by different combinations of the basis functions. Another advantage of this scheme is that it is a very good basis for visuo-motor coordination based entirely on "force fields" [8].

5 Some Experimental Considerations

For reasons of space we did not include a detailed description of our experimental results. Here, we prefer to give a flavour of the "developmental approach" which has, potentially a much wider scope than the specific experiments we are currently conducting. On the other hand, we will briefly mention some aspects of sensori-motor coordination that are focus of our experiments.

The first aspect is related to gravity compensation. The goal here is to design a system which, without knowing its own mass, could: i) learn how to compensate for gravity; ii) cope with (adapt to) variation in the external dynamic and kinematic parameters (e.g. masses, external load, joint length etc.).

The second aspect is more related to visuo-motor coordination and continues what has been proposed in [8] and (even if from a different perspective) in [10]. To explain our approach let's think to a visually-guided reaching task. A traditional way of solving this problem is to use vision to extract the 3D position of the object to be grasped (and its trajectory if the object is in motion). The approach we are investigating is different in the sense that, what we are actually implementing, is an arm controller directing the end-point toward the visual fixation point. In principle, the position in space of the fixation point with respect to the shoulder is totally defined by the eye-head position. In this sense, the fixation point could be seen as the "end-effector" of the head-eye system. If we assume that vision is "simply" acting so that the object to be grasped is fixated, grasping could be achieved by mapping head-eyes angles (and their trajectory in space) into hand position (and trajectory), i.e. by mapping eye-head motor primitives into arm's motor primitives. We called this approach motor-motor coordination.

6 Final Remark

As a concluding remark we would like to stress the relevance of a much stricter relationship between *neuroscience* and *robotics*. Learning from nature is certainly not the only way of building intelligent autonomous systems and future implementations may not be very anthropomorphic. However if the intention is to move robots outside factories and to design them so that they could cooperate with humans, it is very likely that we should give more attention on how humans are made and operate. Using legs instead of wheels has huge consequences not only on how to control locomotion but also on how we perceive and reason. Some of these aspects have been extensively studied by neuroscientist and we should give a closer look to their findings. On the other hand, the practical issues related to building intelligent artificial systems may be the only way to test hypotheses and studying the relationship between brain and behaviors.

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