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Towards Development of Biomechatronic Tools for Early Diagnosis of Neurodevelopmental Disorders

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Abstract— **This paper introduces Neurodevelopmental Engineering, a new interdisciplinary research area at the intersection of developmental neuroscience and bioengineering. Specifically, it presents current results of the design and development process of a set of instrumented toys equipped with a variety of sensors for behavioral analysis of infants in minimally structured environmental conditions. First the multidisciplinary design approach is presented, then the detailed functional and technical specifications of the proposed biomechatronic toys and of their scenarios of use are described. Finally, a clear picture of ongoing implementation of the proposed technology is provided together with preliminary results of verification tests.**

I. Introduction

Neurodevelopmental Engineering is a new interdisciplinary research area at the intersection of developmental neuroscience and bioengineering aiming at providing new methods and tools for:

- understanding neuro-biological mechanisms of human brain development
- quantitative analysis and modeling of human behavior during neuro-development
- assessment of neuro-developmental milestones achieved by humans from birth onwards;
- studying neuro-developmental disorders;
- conceiving new telematic, mechatronic and robotic components and systems for applications on infants and toddlers, which can be used also in ecological conditions for long periods of time;
- investigating ethical, epistemological and social implications related to this area.

Main application fields of Neurodevelopmental Engineering are:

- New clinical protocols and standards for early diagnosis, functional evaluation and therapeutic treatments of neuro-developmental disorders;
- New generations of educational, interactive toys which can provide adequate stimuli and guidance for supporting the physiological neuro-development process

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This technology is expected to be also useful in the long term for developing new tools, e.g. toys, which can sustain, in ecological scenarios, the regular development of motor and cognitive abilities of the child, based on a rigorous scientific approach.

Thought-in-Action (TACT) project is a European funded, three-years project which, in line with the philosophy of Neuro-Developmental Engineering, aims at designing and implementing new methods and devices to evaluate basic patterns of goal-directed actions in normally developing babies, both under laboratory and naturalistic conditions, in order to establish standards against which development of infants at risk for neuro-developmental disorders, particularly autism, can be measured, with the aim of detecting early signs of disturbed development.
The TACT project aims at developing methods and devices that improve our ability to assess:

- basic sensorimotor integration / patterns of gaze;
- expression of emotions;
- social communication;

in infants.

A. Scientific Background on Neurodevelopmental Disorders

Autism is a behavioural disorder, with onset in childhood, which is characterized by deficits in three basic domains: social interaction, language and communication, and pattern of interests. There is no doubt that autism has a strong genetic component, and that biological disease mechanisms leading to autism are already active during foetal development and/or infancy, as demonstrated, for example, by the abnormal pattern of brain growth during late foetal and early postnatal life (see [3], for a review). Autism is usually diagnosed at the age of 3 years, in many cases after a period of seemingly normal neurological and behavioural development. The diagnosis of autism is purely clinical, there are no laboratory tests to confirm or disprove the diagnosis. It has been recognized that, although typical autism is not associated with major neurological deficits, autism has characteristic manifestations in the *perceptual and motor domains*.

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Motor impairments in autism include deficits in postural reflexes [6], [11], [7], repetitive, stereotyped movements and awkward patterns of object manipulation, lack of purposeful exploratory movements (see e.g. [9], gaze abnormalities [12], unusual gait pattern [2], and alterations of movement planning and execution, which express themselves as "hyper-dexterity" [10], [5]. Motor abnormalities may be observed retrospectively in infants who later develop the autistic syndrome, on the basis of home-made movies made during the first year of life [13], [14]. These clinical observations are consistent with a large body of evidence of subtle structural and functional abnormalities of cortical and subcortical neural systems involved in *movement planning and execution*, such as the prefrontal cortex, the basal ganglia and the cerebellum (see [3], for a review).

The purpose of our project is to develop technological platforms and methods to extract more information on perceptual and intersubjective capacities of human infants than is currently possible; this information could be later used for early diagnosis of developmental disorders. In particular, diagnosis of ASD is currently made at 3 years of age; ADHD is always considered as an alternative diagnosis of "high functioning" autism; Tourette syndrome is diagnosed at age 7 or later. ASD is therefore a natural candidate for demonstrating the validity of the approach proposed in the TACT project. Given the affinity of neurodevelopmental disorders, in term of their neural origin and behavioral manifestation, results achieved for autism would be extendable to other neurodevelopmental disorders, and vice versa.

B. The TACT Project

The TACT project has been devised in order to allow a closed-loop dialogue between biomedical and bioengineering researchers, with a common and rigorous methodological approach based on:

- the definition of novel scientific hypotheses on ASD early diagnosis;
- the customised design of new mechatronic technologies enabling the validation of such new hypotheses;
- the execution of multisite experimental tests.

Results from ongoing experiments are expected to continuously provide a flow of new knowledge and hypotheses to be incorporated into the design of a new generation of technologies, e.g. toys and wearable devices, which in turn will allow the design of new scientific experiments all through the project lifecycle.

We will follow a *step-by-step approach* going from more basic to more complex smart toy devices.

II. Functional and Technical Specifications of TACT Devices

Since its early conception, the TACT project devised the use of sensorised toys as a means of studying a childs activity. Toys are age-specific but, among many possible choices, rattles and balls seemed the ones that could be used equally well with all children in the 0-24 months range of age. At least for the first generation of TACT devices, commercially available toys will be used and equipped with sensors. The purpose of this choice is twofold:

i) allowing to have prototypes and therefore run experiments as soon as possible;
ii) developing a sensing unit which is independent of the specific shape of the toy and that can then be embedded in other toys to allow use in various experimental scenarios (including experiments with *older* children).

Toys such as rattles and balls can in fact be used in a very broad set of experimental scenarios but for the first TACT platform, attention was particularly paid to define operating scenarios which would allow studying specific biomechanical aspects of the movements of infants during tasks with a minimum set of involved "free" variables, especially considering that only few data of this kind are available in literature at least as long very young children are concerned. A key element in choosing a toy is its *affordance* , i.e. its perceived usage inferred from its appearance and look [8]. The shape of the toy suggests the use to be done with the toy itself and can, in part, guide the child to perform certain movements instead of others[1] (i.e. shaking in air vs. random banging on objects around the child). After careful examination of different commercial rattles, we opted for a maracas-like shape since it suggests shaking rather than banging (as an hammer-like object would). In order to reduce the number of "free" variables (i.e. the child's choice of orientations, grasping patterns etc. . . when playing with toy) a maracas-like rattle offers a pen-like handle, encouraging thus only a limited number of grasping hand-configurations.

Differently from the RATTLE, the choice for the BALL is straightforward: spherical and small enough to be handled with a single hand also by a 6 month old child. Both RATTLE and BALL devices should allow monitoring kinematical patterns arising during the playful activity, allowing for example monitoring imitative and rhythmic skills of the child as well as monitoring the grasping force/pressure. Musical feedback is considered important not only for motivating the child to keep playing with the toy but also as a programmable/adaptive way of guiding the game. Attractive sounds/melodies may be associated with specific movements, inviting thus the child to repetitively perform such movements. The RATTLE shall have on-board musical capabilities while for the BALL, in order to reduce size and weight, music will be generated off-board.

A. Experimental Scenario

The child is sitting on a orthopedic high chair constrained so that only the upper limbs are free to move (torso is also fixed to the chair) only for 6 months old children. For 12 and 18 months: belts applied only to lower extremities. Belts should be used for safety purposes. A caregiver - possibly mother - is sitting next to the child. A toy is placed on

[1]The caregiver, of course, will also guide the game, imitation is a key element to be exploited in designing games.

a support along the midline at a predetermined distance, according to the length of upper limb, on the desk which is shaped as in Fig.1:

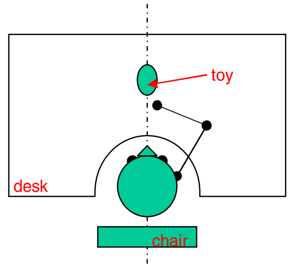

Fig. 1. First experimental scenario (top view)

The toy can be either a RATTLE and BALL. The caregiver (sitting next to the desk)

- shakes the toy to draw the attention of the child and
- places the toy on a support (neutral color) fixed on the table, used to keep the toy in place

The child is expected to perform the following actions:

- reach for the toy
- grasp it
- lift it up
- freely shake it (for a while)

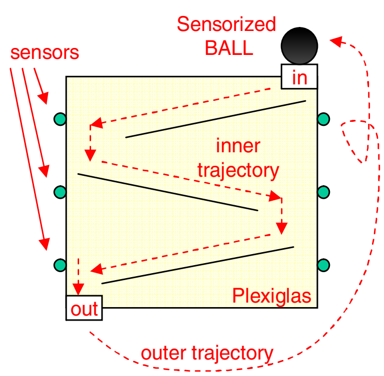

Fig. 2. Second experimental scenario: front view of the proposed game involving the sensorized BALL

A second experimental scenario is shown in Figure 2. The sensorized BALL can be inserted only in the top-right hole and, after a fixed inner trajectory, exits always from the bottom-left hole. During the inner trajectory the child can only watch the ball falling down (Plexiglas transparent material). As the ball exits, the child can reach for it, grasp it and re-insert it via the top-right hole. The outer trajectory is totally up to the child. The task starts with the caregiver showing the child how to play with the system. The game is meant to be repetitive, i.e. the inner trajectory never changes and although the outer trajectory is up to the child, the start and the end points are fixed. The child should be able to repeat the game several times (at least 5). Measurements of interest:

- ball trajectory, at least the outer one - movement accuracy, presence/frequency of shaking
- force/pressure exerted on the ball during grasping
- childs *gaze*[2] during inner trajectory (the Plexiglas allows watching but not touching

Both RATTLE and BALL will be provided with the following set of sensors:

- kinematics sensing unit
- force sensor unit

B. *Measuring Kinematics*

Measuring movements can be rightfully considered part of *motion tracking*. Motion tracking can count on a host of different technological solutions, operating on entirely different physical principles, with different performance characteristics and designed for different purposes. As shown in [15] there is not a single technology that can fit all needs. Each application defines the best technology to be implemented.

The most appealing technology, from a TACT perspective, is represented by the *sourceless* inertial/magnetic sensing for orientation tracking[3]. Such a technology is based on accelerometers and magnetometers used to sense respectively the gravitational and the geomagnetic field. Gyroscopes can also be used to enhance performance and gain robustness. Gravitational and geomagnetic fields can in fact be used to estimate rotations of a rigid body relative to an earth-fixed coordinate frame, see [1] and references therein.

In this sense it is sourceless since, differently from many other technological solutions, it does not depends on artificial external fields. The gravitational and geomagnetic fields are present everywhere on earth, such a technology is perfectly suitable to non-structured environments such as clinical centers, kindergartens and homes. Use of such technology in clinical applications can be found in [4]. Accelerometers are not only sensitive to the gravitational field but to acceleration as well. For this reason, in combination with gyroscopes, translational acceleration of the toy can be also detected. The information derived from the inertial/magnetic sensing unit can thus be used to depict trajectories in space of the toy as well its orientation. Miniaturized commercial accelerometers, magnetometers and gyroscopes will be used in conjunction with custom acquisition electronics so to be embedded in commercial toys. In particular:

- ADXL203 2-axis MEMS accelerometer (Analog Device)
- ADXRS300 1-axis MEMS gyro (Analog Device)
- HMC2003 triaxial magnetometer (Honeywell), each contains a 1- axis and 2-axis magnetometer.

[2]Sensors on the side can track gaze as if the child was watching a TV screen, the game is purposely designed to be 2-dimensional without distorting the 3D physical feeling.

[3]Commonly available (also to TACT partners) motion tracking systems typically provide position of points (markers) in space, orientation is consequently derived from the position of a group of non-collinear points. As dimensions of objects (or body parts) decrease, also accuracy in determining orientation decreases. Orientation tracking is therefore given a higher priority. In line with the specifications of such motion tracking systems, TACT devices are designed to capture movements at a rate of 100 Samples/Sec. Angular resolution of $0.1^o\ RMS$ and static accuracy of 1^o are technologically at reach.

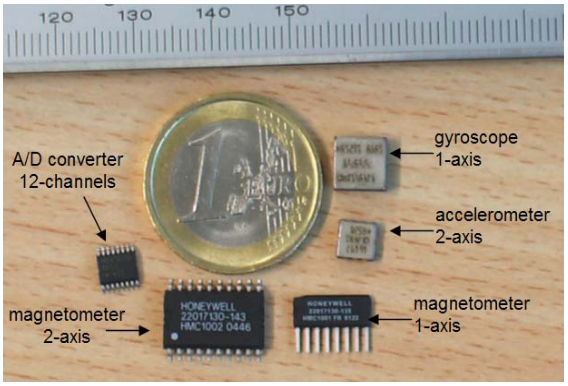

Fig. 3. Set of sensors embedded into the TACT tools

Fig.3 shows the commercial sensors and acquisition electronics to be embedded into TACT toys while Fig.4 show the architecture of the force/kinematics sensing unit plus the musical feedback unit.

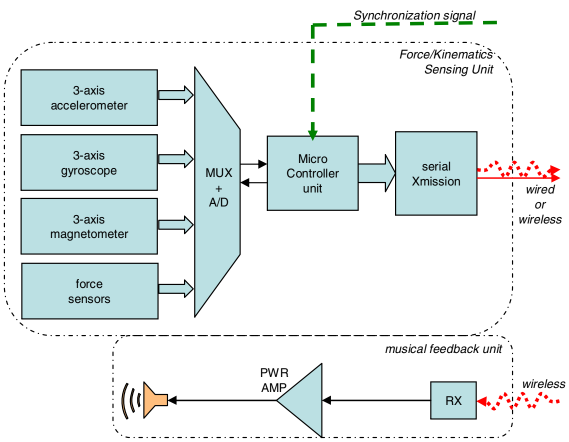

Fig. 4. Architecture of the mechatronic toy

C. Force Sensing

Presently most force sensors use piezoresistive materials to detect the applied force. For the TACT applications, suitable force sensors are represented by the QTC sensors that allows a different approach to be taken. QTC is essentially a non-conductor in its normal state. However, under pressure, QTC starts to conduct and its resistance drops to below 1 ohm in a smooth, predictable and totally reversible way. QTC Force Sensors are commercially available from Peratech. They are constructed using standard lamination processes, so sensors of almost any size and shape can be made and the response curve of the sensors can be tuned to the application by varying the composition of the QTC layer. QTC Force Sensors can be supplied with or without a variety of connectors to allow flexible configuration.

III. Conclusions

In this paper, ongoing development of a new platform for behavioral analysis of infants based on the integration of multisensory data has been presented. Three different new concepts of instrumented toys (RATTLE, BALL and apparatus in Fig.2) have been introduced and their specifications and current status of implementation have been described. Preliminary tests on the BALL and RATTLE early prototypes in a kindergarten with real end users (infants) demonstrated full accepability of the proposed concepts and encouraging technical performance in terms of measurements of orientation in 3D space. Such performance is largely compatible with the requirements of envisaged application of this system as a set of new tools for investigating the emergence of neurodevelopmental disorders. Next steps of the research are aimed at releasing the final prototypes of the proposed toys by December 2006 and to subsequently start experimental trials in three infant clinical labs located in Europe.

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