2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Design of a Sensorized Ball for Ecological Behavioral Analysis of Infants

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Abstract— **Neuro-Developmental Engineering is a new interdisciplinary research area at the intersection of developmental neuroscience and bioengineering. Applications can be found in early detection of neuro-developmental disorders via a new generation of mechatronic toys for assessing the regular development of perceptual and motor skills in infants, in particular coordination of mobile and multiple frames of reference during manipulation. This paper focuses on the design of a novel mechatronic toy, shaped as a 5 cm (diameter) ball, i.e. small enough to be grasped with a single hand by a 1 year old child. The sensorized ball is designed to embed a kinematics sensing unit, able to sense both the orientation in 3D space and linear accelerations, as well as a force sensing unit, to detect grasping patterns during manipulation. Dimensioning of batteries able to operate for 1 hour during experimental sessions as well as a wireless communication unit are also included in the design.**

I. INTRODUCTION

Neuro-Developmental Engineering (NDE) is a new interdisciplinary research area at the intersection of developmental neuroscience and bioengineering aiming at providing new methods and tools for: i) understanding neuro-biological mechanisms of human brain development; ii) quantitative analysis and modeling of human behavior during neuro-development; iii) assessment of neuro-developmental milestones achieved by humans from birth onwards.

One of the most challenging applications of NDE is *early detection* of neuro-developmental disorders such as Autistic Spectrum Disorders (ASD), a behavioral disorder with onset in childhood, usually clinically diagnosed at the age of 3 years, i.e. only *after* language development. There is recent evidence that early signs of ASD can be found in infancy, especially in the *perceptual and motor domains* [20].

Specifically for the perceptual and motor domains, recent studies on *tool-use development* in infants found that achievement of certain developmental milestones involves coordination of multiple and mobile frames of reference [15]. This kind of coordination is necessary in games such as piling up cubes, inserting objects in holes etc...

For this reason, among the large number of kinematic variables we chose to focus on *orientation* in 3D space of objects, especially in relation to vertical lines (where gravity acts) and horizontal planes (tables, ground etc...), as well as on *linear accelerations*, typically involved in shaking and banging.

Toys such as rattles, balls and cubes can in fact be used in a very broad set of experimental scenarios but for the first 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.

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Technologies were selected that do not require costly equipment (stereo-photogrammetric systems) and/or a structured environment (movement analysis), that work in *ecological* scenarios (e.g. at home) and that can be operated by minimally trained personnel, e.g. the child's caregiver.

In this perspective, orientation tracking based on inertial/magnetic sensors [16], [2], [22], [4] represents a promising *sourceless* technology since orientation of a rigid body can be measured solely relying upon gravitational and geomagnetic fields, which are present everywhere on earth.

Accelerometers, magnetometers and gyroscopes are available in packages small enough to be worn or embedded into small toys and can be used to track position/orientation in unstructured environments.

II. PRELIMINARY EXPERIMENTAL DATA

Preliminary studies have been conducted with infants at a local kindergarten in order to assess acceptance of toys with different shapes, materials, size and weight.

Preliminary *quantitative* experiments have been performed using a commercial device (MTi from Xsens, containing inertial/magnetic sensors) embedded into a soft cube large enough to contain it (each side was $10\,cm$). Several children were let to play with it while raw data (i.e. data from the 3-axis accelerometers, 3-axis magnetometers and 3-axis gyroscopes inside the MTi) were being downloaded on a PC (connected via a USB cable to the sensorized cube) and while the playing session was being filmed on camera.

Such experiments showed that:

i) children were often distracted by the wire, so a *wireless* connection would be highly preferable;
ii) the cube was *too large* so that children would rather adopt a bimanual manipulation, or use the wire to lift up the toy;
iii) a *ball*, because of its symmetry, would be preferable to a cube in order to reduce the number of possible grasping patterns.

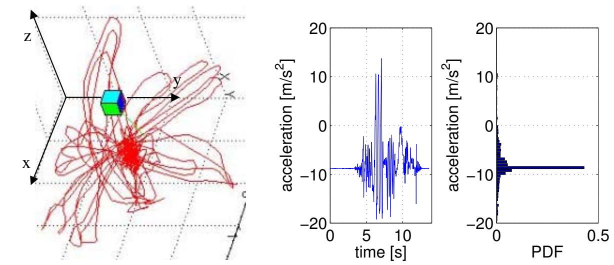
Nevertheless, some moments could be filmed where the child actually played with the toy. Data from MTi were later analyzed allowing to reconstruct the orientation of the cube as well as its linear accelerations during manipulation.

The video-clip accompanying this paper shows the superposition of a virtual cube (whose orientation was later computed off-line from raw data) and the real cube, as the latter is being manipulated by a child.

The ideas behind the complementary filter used to derive the 3D orientation and linear accelerations from the raw data are described in the next section.

Another preliminary test, whose results are also discussed in the next section, was performed to estimate an upper bound of the range of linear accelerations due to human movements. In particular, the sensorized cube was subjected to vigorous shaking by an adult.

Accelerometers sense linear accelerations as seen from the object (toy) point of view, while the complementary filter allows extracting linear accelerations as seen from the experimenter (e.g. clinician) point of view. Shaking was intentionally performed along three orthogonal axes and this is clearly visible in Fig. 1-a.



a) b)

Fig. 1. (a) Vigorous shaking of a sensorized cube along three orthogonal axes. (b) *Left:* time plot of the acceleration as sensed along the vertical axis (comprising the gravity bias). *Right:* Probability Distribution Function (PDF) estimate.

III. Functional and Technical Specifications

Previous considerations lead us to devise a wireless toy shaped as a ball capable of sensing kinematics (i.e. orientation, and linear accelerations), grasping forces during manipulation and *small* enough to be handled with a single hand by a child as young as 6 months old. This can be quantified in a ball's diameter $\leq 5\,cm$.

The wireless constraint also means that the device should be autonomous in terms of energy, i.e. it should include batteries and should be able to run for a sufficient time. Experiments involving children, in particular very young ones, usually can only last a few tens of minutes, in any case they never exceed one hour. This will be also considered later when selecting the proper battery.

A. Measuring Kinematics

Motion tracking can count on a host of different technological solutions and as shown in [21] there is not a single technology that can fit all needs.

The most appealing technology, from an *ecological* perspective, is represented by the *sourceless* inertial/magnetic sensing for orientation tracking. Such a technology is based on accelerometers and magnetometers used to sense respectively the gravitational and the geomagnetic field as well as on gyroscopes used to enhance performance at higher frequencies. Gravitational and geomagnetic fields can in fact be used to estimate rotations of a rigid body relatively to an earth-fixed coordinate frame, as shown in [5], [6].

Complementary filters and Kalman filters have traditionally been used to derive 3D orientation (attitude) from inertial and magnetic measurements [2], [16], [22]. With reference to Fig. 2 whose details can be found in [6] and [21], inertial and magnetic sensors embedded in an object (e.g. a toy) provide measurements of "vector" quantities (e.g. accelerations, angular velocities and magnetic field) in a frame of coordinates relative to the object itself (*moving frame*). On the other hand, certain quantities are only known in a *local frame* of coordinates. For example, the gravity vector $\vec{G}$ can be expressed as $\vec{G} = [0\ 0\ -g]^T$ (where $g = 9.81 m/s^2$) only in the local frame, where gravity also defines important concepts such as "vertical" and "horizontal".

Human movements, especially in the case infants, are characterized by accelerations much smaller if compared with the magnitude of the gravitational field (g). Only during high speed impacts (e.g. banging) large accelerations can be generated but impact dynamics is out of the scope of this research.

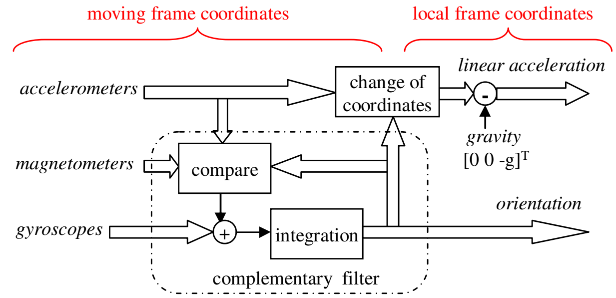


Fig. 2. Complementary filter approach to orientation tracking.

The full scale range of a sensor, given the full scale ranges of a set of available sensors, is selected as the minimum one containing the all signal excursions. A smaller range may in fact lead to saturation when certain operative conditions occur, while a larger range would reduce sensitivity.

As mentioned earlier, a simple test (see Fig. 1-a) was performed in order to estimate a proper scale range for human movements a sensorized cube was vigorously shaken by an adult for a few seconds, in particular in the vertical direction (worst case since gravity adds up) and accelerations thus produced were analyzed.

Fig. 1-b shows (left) the time plot of the acceleration as sensed along the vertical axis and (right) its relative Probability Distribution Function (PDF) estimate[1]. Since the experiment was carried out by an adult, it is realistic to consider that an infant would never exceed the $\pm\,20m/s^2 \approx \pm 2g$ range of accelerations.

As for the magnetometers, since only the geomagnetic field (about $0.6\,gauss$, see [7]) needs to be measured, the full measurement range should be in the order of $\pm 1\,gauss$.

Measurements for gyroscopes, as shown in Fig. 2, after a correction are directly fed into the "integration" block. It can be shown [3] that gyroscopes are the main responsible for tracking orientation when fast rotations are involved. Movements such as wrist rotations, considering the application of interest (hand-held toys), can be quite fast. Saturation of gyroscopes would result in a problematic loss of tracking and therefore, given several commercially available gyroscopes with full scale ranging from $\pm 150\,deg/s$ to $\pm 1200\,deg/s$, the maximum scale range ($\pm 1200\,deg/s$) was selected.

B. Bandwidth, Noise and A/D Conversion

Although ecological devices should be primarily designed to work in unstructured environments, they could also be used in research laboratories (e.g. laboratories investigating developmental disorders). It is not uncommon for such laboratories to be equipped with traditional marker-based motion analysis systems such as stereo-photogrammetric ones. Such systems consist of a set of cameras (often infrared ones) which are used to film the experimental session from different view-points. Such cameras, at least as long infants movements are concerned, are typically used to film the scene at $100\,frames/s$, although some systems may also allow higher frame rates.

In line with such specifications, since our new devices could be used in conjunction with stereo-photogrammetric systems, a $100\,Hz$ sampling frequency was considered to be the appropriate one. This translates into an anti-aliasing filter cut-off frequency at $50Hz$.

[1]Computed via the `hist()` MATLAB function.

Higher sampling frequencies would not be a technological problem *per se* but since signals of interest (movements of humans and in particular of infants) are confined well within a few tens of Hz, a larger bandwidth would only increase the noise level resulting in a loss of *resolution*.

As an example, consider the accelerometer ADXL103 from Analog Device. Datasheets describe its noise as being white Gaussian noise, quantified in a typical noise Power Spectral Density (PSD) equal to $PSD = 110\mu g/\sqrt{Hz}$.

After the low-pass (anti-aliasing) filter with bandwidth $BW = 50\,Hz$, the Root Mean Square (RMS) σ_g is given by

$$\sigma_g = PSD\,\sqrt{1.6\,BW} \approx 10^{-3}\,g$$

where 1.6 is a correction term when a 1-pole low-pass filter is used.

Considering, from datasheets, a sensitivity $k_g = 1V/g$, the output voltage RMS is:

$$\sigma_{V_g} \approx 1mV$$

Once the output voltage RMS is estimated, the proper number (N) of bits for A/D conversion can be also determined. An N-bits ADC (A/D Converter) working at $5V$ can discriminate voltage differences no less than $5/2^N\,V$. In ideal (noiseless) conditions, the larger N the better the ADC resolution, but when noisy signals are considered, resolution cannot be better then the noise RMS. Choosing $N = 12$ leads to $5/2^{12}V \approx 1mV$, which is comparable with the noise RMS $\sigma_{V_g} = 1mV$.

C. Force Sensing

Measuring force essentially means measuring the displacement or the strain induced by a force in an instrumented deformable structure such as a membrane or a cantilever. [10] The wide variety of configurations and design options adopted in force and tactile sensing technology originates from the exploitation of many different transduction effects and materials which are capable of mechano-electric, mechanomagnetic and mechano-optic conversion [9], [10], [14], [17], [18]. Conventional commercial force sensors often consist of a beam or a diaphragm to which a thin-metal film strain gauge or a semiconductor strain gauge is attached. The force is then detected by measuring the resistivity change in the strain gauge which varies in accordance with the applied force.

The fingertip forces exerted by children during manipulation tasks was deeply investigated in literature [1], [19] especially with respect to the assessment of functional abilities of children with cerebral palsy (CP) [12], [11], [13]. It is known that the control of fingertip forces during object manipulation in healthy children generally approximates adult coordination between the ages of 6 and 8 years. In contrast, 6- to 8-year old children with hemiplegic or diplegic CP often have a force coordination resembling that of 1-year-old children. Some authors report experimental data from which the fingertip forces during manipulative tasks (such as grip-and-load) is approximately in the range $20 - 50\,N$ [12], [13]. Unfortunately most of these investigations were not conducted on infants but rather on children older than of 3-4 years; therefore, up to our knowledge, there is a general lack of reference data concerning the force exerted during manipulation in infancy. The clinical requirements of the force sensing devices were identified in the following points: $i)$ Dynamic creation of an accurate spatial map of the contact; $ii)$ Measurement of the force magnitude with an adequate level of spatial resolution.

In order to meet these clinical requirements a new sensor has been purposively developed taking advantage of a new commercial smart material. (i.e. the Quantum Tunneling Composite)

The Quantum Tunneling Composites (QTCs) are a very recent technological achievement consisting of a flexible polymer that can turn from an nearly perfect insulator into a nearly perfect conductor according to the force applied. Differently from conventional commercial force sensors, the QTCs does not make use of the piezoresistivity phenomenon as for the transduction principle. At the same time, the conduction process occurring in QTCs differs even from the ordinary process occurring for standard composites (i.e. percolation) which are usually made from polymers filled with carbon. Instead of carbon the QTCs contain tiny metal particles that never come into contact but when a compressive force is applied to the composite the metal particles get very close each other. At this stage the Quantum Tunneling phenomenon is activated between the metal particles and the material becomes a nearly perfect conductor that is capable of conducing very high currents. The QTC is a flexible "rubber-like" material that can be easily adapted to arbitrary shapes. The new sensor represents the core element of the tactile sensing unit and will allow a spatial resolution comparable to the one of human skin; (approx. $2\,mm$) [8]. This is considered to be fundamental for discriminating both the force exerted by the infants and the actual shape of grasping. Furthermore, the high temporal resolution of the proposed sensor will allow the detection and measurement of both grasping and manipulation.

IV. Design of a Sensorized Ball

In this section the design of a sensorized device, here after called BALL, according to specifications given in the previous section is described. Such a device is shaped as a sphere with a $5\,cm$ diameter. The BALL device shall comprise: $i)$ kinematics sensing unit; $ii)$ force sensing unit; $iii)$ pre-processing and data acquisition unit; $iv)$ wireless transmission unit; $v)$ power unit.

Only the force sensors will be in the outer part of the device (a force sensitive layer covering the outer part for sensing grasp and manipulation), all the rest shall be embedded inside.

A. Kinematics Sensing Unit

The kinematics sensing unit comprises: 3-axis accelerometers, 3-axis magnetometers, and 3-axis gyroscopes. Several highly miniaturized components are available on the market, most of which providing a pre-amplified analog output, ready to be converted into a digital signal.

Among several possibilities, the best solution in terms of compactness was represented by MAG3, a microfabricated device from Memsense[2] integrating all required sensing capabilities (9 channels in total) assembled in a highly miniaturized case (less than $17.8\,mm \times 17.8\,mm \times 10.2\,mm$). Needless to say that this is also the most expensive solution.

The alternative would be assembling different sensors as shown in Fig. 3 where one half of the outer structure of the BALL is shown (for comparison) together with one MAG3 device as well as with another solution[3] comprising a 3-axis magnetometer (HMC2003 from Honeywell), three 1-axis gyroscopes (ENC-03 from Murata) and a 3-axis accelerometer (ADXL300 from Analog Device). Although functionally equivalent, the second solution is more cost-effective but clearly less compact.

Although more expensive, the MAG3 device was preferred over other solutions mainly for two reasons:

[2] In particular: MAG02-1200S050 ($\pm 2g$, $\pm 1200\,deg/s$, $50Hz$-bandwidth)

[3] There exist many several possibilities of assembling different components, all more or less equivalent to the one shown in Fig. 3.

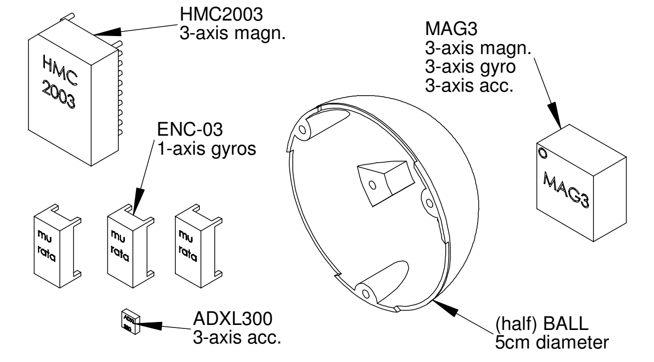


Fig. 3. Comparison of dimensions of different solutions for the kinematics sensing unit. Dimensions are in scale. MAG3 offers a real advantage when it comes to system integration, the $5\,cm$ hemi-sphere is shown for comparison purposes.

i) a more compact solution would leave more space for the remaining electronics;

ii) when assembling different inertial or magnetic sensors, special care should be paid during the alignment of the sensitive axes of each sensor. Failure to do so directly translates in errors during orientation tracking. MAG3 guarantees very small alignment errors;

As for calibration, the MAG3 device as well as other commercial accelerometers and magnetometers have special pins that can be used to produce a known excitation against which the output signal can be calibrated. Especially in the case of magnetometer (where this extra pins are used to generate a magnetic field), large currents are required which is unsuitable with the application of interest.

Novel calibration procedures have been set up which do not require any additional electronics and that can be performed in unstructured environments by non trained personnel, details can be found in [4].

B. Force Sensing Unit

In our realization the tactile sensing unit uses a QTC in the form of pills. The sensor itself consists of a two-dimensional array of QTC pills that are assembled in different configurations onto a Kapton flexible surface. Each QTC pill is $3.6\,mm \times 3.6\,mm \times 1\,mm$ in size, weights $0.04\,grams$, senses forces in the $0-100\,N$ range and shows a resistance in the $1-10^{12}\Omega$ range.

The proposed arrangement of the array of QTC pills allows the required spatial resolution (approx. $3\,mm$) thanks to the very small size of the sensor. Moreover, the array is packaged and mounted onto a Kapton flexible circuits, thus allowing a great suitability for sensorizing non-planar surfaces such as in the can of the BALL device. Ideally, the force should be applied perpendicular to the flat face of the pill; however the pills also work if the force is applied at an angle, as long as there is sufficient component of force in the perpendicular direction.

In the practical realization of the sensor we investigated the trade-off between the mechanical robustness of the sensor and the flexibility of the structure that is required for matching non planar surfaces. Two different connections of the QTC pill to the conditioning electronics were designed and investigated: a "sandwich-like" structure and a planar structure. For both structures the circuit tracks have a width of $200\,\mu m$ and they are spaced by a $100\,\mu m$. This results in an overall dimension of, respectively: $17.1\,mm$ wide, $14.1\,mm$ long for a 16 sensors sandwich-like structure array and $21.9\,mm$ wide, $11.1\,mm$ long for a 16 sensors planar structure array.

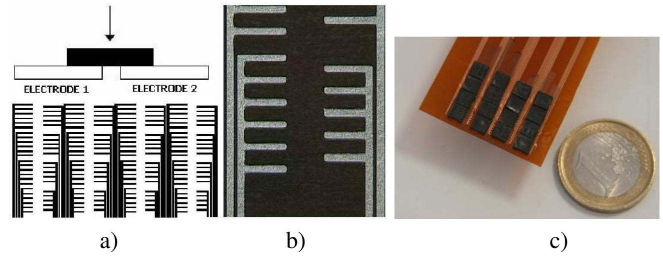


Fig. 4. (a) Design and realization of the planar structure: schematic design (*top*), CAD design of the array (*bottom*). (b) Microscopic photo of the actual circuit (*right*). (c) Actual realization of the planar sensor.

On the sandwich-like structure, two different Kapton flexible circuits have been realized and the QTC pill force sensors were positioned in between of the two sheets. This is the simplest mounting arrangement. The main advantage of the sandwich-like structure is the greater robustness (sensors are not in direct contact with force), while, as drawbacks we remark that: a) the stiffness of the kapton circuits results on a global smaller sensitivity of the force sensor array, b) the connection of the two Kapton circuits to the conditioning electronics results rather complicated. Considering these limitations and given that the pills are also capable of conduction across the surface of the material, we decide to adopt the planar configuration that is reported in Fig. 4-a and 4-b.

In this configuration, the separation between the electrodes is on the plane of the Kapton circuit and may be set as a small fraction of the pill dimension. The QTC pills were simply glued between the contacts and the resulting structure is the single flexible layer that is depicted in Fig. 4-c. As compared with the sandwich like solution, this realization turned out to be more flexible and more sensitive to small applied forces.

The description of early prototype was completed by performing the sensor characterization. This procedure was executed using a tensile compression testing machine (Instron) for a fine calculation of the relationship between the applied force and the resistance drop in the actual sensor structure.

The voltage drop across each QTC pill (i.e. $Vout$) was measured using the simple voltage divider represented in Fig. 5-a.

In this circuit the reference resistance (R1) was $198.5\,k\Omega$ and the input voltage (Vin) was $10V$. The tensile testing machine operated in compression and data were acquired using LabView. The responses of the QTC pills (i.e. $Vout$) were measured by applying controlled compression forces such as those reported in Fig. 5-b (bottom) and spanning all the operative range of the sensor ($0-100\,N$).

A typical example of the relation between the compressive force exerted by the machine and the corresponding output voltage across the sensor is reported in Fig. 5-b (top).

As it may be devised from Fig. 5 (top), $Vout$ remains approximately constant when applied forces are below $15\,N$ whereas for increasing forces Vout increases; for forces above $40\,N$ the sensor saturates and behaves like a short-circuit. It is worth noticing that approximately in the range of $20-40\,N$ the sensor shows a roughly linear relation between the voltage drop and the force exerted.

In order to tune the operative range of the QTC pill, we also designed and realized different mechanical structures (i.e. a truncated pyramid and a semi-sphere) that were assembled on each pill. These devices were glued on the pills and the resulting structure

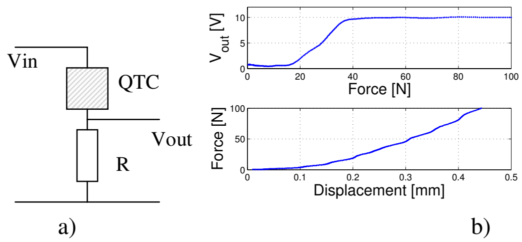


Fig. 5. (a) Schematic representation of the experimentally tested configuration. (b) Time plot of the output voltage (*top*) and force vs deformation plot (*bottom*).

was then coated with a silicon rubber for insuring an adequate robustness during manipulation.

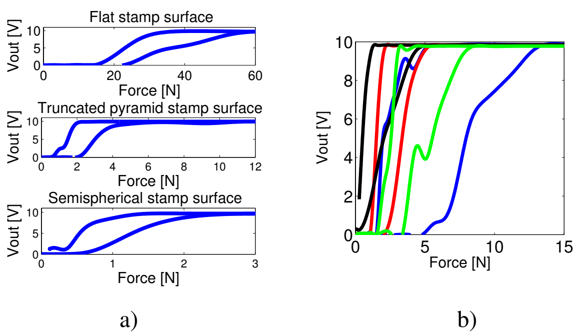


Fig. 6. (a) Effect of different mechanical devices for tuning the operating range of the QTC pill. (b) Variability of the force-voltage curve for different pills (*experiment performed with the truncated pyramid device*).

As expected, the effect of the mechanical devices was to lower the activation threshold of the pills. Roughly speaking the use of the truncated pyramid moved the QTC operating point from $20-40\,N$ to $2-8\,N$, whereas the use of the semi-sphere moved the QTC operating point from $20-40\,N$ to $0.5-2.5\,N$. In Fig. 6-a we report a typical example of the different operating curves.

Finally, the possible variability across the array was also addressed by visual inspection of the Force/Voltage curves obtained for different pills. Variability over pills was generally low; although, as reported in Fig. 6-b, one of the sensors showed a significant difference from the others. This is explained by a possible imperfect gluing of the pill on the Kapton circuit.

Interestingly, the different working ranges obtained are compatible with many experimental data reported for children during manipulative tasks [12], [11], [13].

C. Pre-Processing, Data Acquisition and Communication

The analog outputs from tactile sensors[4] need to be filtered and buffered before numerical conversion. By using Surface Mounted Devices (SMD), a 1-pole ($50Hz$), RC, low-pass filter as well as a buffer for each analog channel can be added in relatively little space.

Data can then be digitally converted via several MAX1238 (low-power, 12-channels, 12-bits AD Converters from Maxim-Dallas). After digital conversion, the MAX1238 transmits data over the standard I2C bus, a 2-wires serial bus. A microcontroller rfPIC12 (from Microchip) is used to: i) sequentially collect data over the I2C bus from every MAX1238 (each identified by a unique address); ii) transmit data wireless to a nearby station. Every $10ms$ (i.e. $100Hz$) a packet is sent containing an identifying code (multiple BALLs may be used in the same session), a time stamp (used for synchronization with other devices), collected bytes data and a final checksum.

[4]The MAG3 device directly provides filtered outputs with a $50Hz$-bandwidth, requiring thus no extra circuitry.

D. Power Supply

Power consumption and supply is a key issue in every portable system. In the case of interest, a power source should be identified that is capable of constantly providing energy for about an hour (estimated maximum time for a recording session) and yet be small enough to fit in $5\,cm$ ball together with the previously described electronics and sensors. Among battery technologies, the Lithium-Ion (Li-Ion) cells exhibit the highest energy density. A single Li-Ion cell provides $3.6V$. Since MAG3 sensor requires $5V$ to operate, at least a two-cells serial configuration is needed together with a voltage regulator. Rechargeable cells are preferred over non-rechargeable batteries because this would allow sealing the device, battery recharge would then occur via connectors before every experimental session. Although Li-Ion cells are widely used for cellphones and other portable devices, only few coin-shaped cells are available. Coins cells have a better chance to fit into a sphere because of their rounded shape. A series of coin Li-Ion rechargeable (Lir) cells is produced by Powerstream Corporation in different sizes. In order to choose the proper one, energy consumption has to be estimated. Most of the energy is consumed by the MAG3 sensor, datasheet report a maximum $57mA$ current ($5V$ operating voltage). The only other power-demanding component is wireless transmission. Datasheets of rfPIC12 report maximum $11.5mA$ current during RF transmission. Other electronics components are very low power. An over estimate of the total current is in the order of $70mA$. To guarantee a continuous 1 hour operation, a minimum cell capacity $C = 70mAh$ is required. Usually, a larger capacity should be considered and according to recommendations from Powerstream:

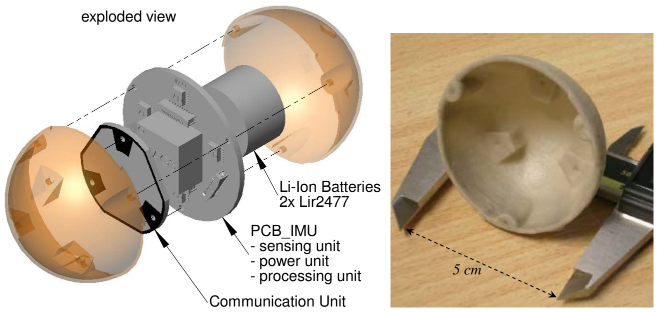
i) Cycle Life: in order to guarantee many life cycles, a cell should never be discharged by more than the 80% of its energy, i.e. a larger capacity $C' = C/0.8$ should be considered;

ii) High Rate Discharge: at high discharge rates the capacity falls steeply. As a "rule of thumb", a 1 hour discharge rate (i.e. fully discharging an $x\,mAh$ cell at $x\,mA$) will reduce by half the available capacity, i.e. $C'' = 2 * C'$;

Previous considerations lead to a required capacity $C'' = 2/0.8 * 70mAh = 175mAh$. The Lir2477 coin cell from Powerstream perfectly fits such requirements. Furthermore, although being the largest in size ($24.5mm$ in diameter and $7.9mm$ in height for a single cell) of the Powerstream Lir series, it is compatible with the dimension constraints of the BALL device.

E. Integration and Rapid Prototyping

After having identified all the most critical components (in terms of size and energy consumption), it is possible to define an integration strategy.In Fig. 7-a, an exploded view of the BALL device is shown containing the main components, for which a 3D model was developed to take into account their maximum space requirements. The structure is composed of 2 hemi-spheres, here after shells. The MAG3 device, being sensitive to linear accelerations, should be placed in a central position with respect to the outer structure. For this reason, the MAG3 will be soldered in the center of PCB-IMU circuit board (visible in Fig. 7-a) which, in turn, will be in between the two outer shells, guaranteeing thus a central position for the



a) b)

Fig. 7. (a) Exploded view of the overall assembly. (b) Outer shell prototype.

MAG3 device. The tactile sensors will be located on the outer part of the BALL. Slots have been purposely designed on the two shells (at the level of "equator") to allow kapton films to make contact with the PCB-IMU (several connectors are visible on the PCB-IMU, surrounding the MAG3 device). Two Lir2477 Li-Ion cells shall be placed (electrically in series) on the other side of the PCB-IMU board, 3D CAD drawings allowed verifying that everything would actually fit once the two shells are sealed together and that there would be enough room for some additional mass purposely tuned to counterweight any decentering of the center of mass. The outer shells of the BALL device were developed via rapid prototyping. In particular, a ZPrinter 310 Plus model from Z-Corporation was used to "print" the two shells out of the CAD files, the result in shown in Fig. 7-b. Such a 3D printing technology, besides accurately reproducing every detail present in CAD drawings, also provides a final result which is mechanically light and robust.

V. Conclusion and Future Work

In this work a sensorized ball was designed for ecological behavioral analysis of infants, an application in the general framework of Neuro-Developmental Engineering. Although primarily designed for use in ecological conditions, the sensorized toy can also be used in research laboratories (e.g. laboratories investigating developmental disorders) in experimental sessions involving multimodal (video, audio, kinematic, tactile etc...) data recordings. In fact, preliminary experiments have been carried out with infants at a local kindergarten where video and kinematic data were recorded separately during an experimental session and, later, superimposed in a video-clip accompanying this paper. Superposition is crucial when multimodal data are being recorded and was made possible by an ad-hoc procedure which can also be used when several sensorized toys are involved.

Such preliminary data also provided functional and technical specifications that guided the design of the whole sensorized ball.

As future work, several prototypes of the sensorized ball as well as of other toys will be developed according to the design guidelines in this paper. The prototypes will be delivered to 4 different clinical sites in Europe and the challenge will be the interpretation of data recorded in ecological scenarios with the aim of detecting potential abnormalities in development.

Acknowledgment

This work was supported by a grant from the European Union, FP6-NEST/Adventure Programme, contract no. 015636, and by a grant from "Regione Lazio" under the "DOCUP 2000/2006 - Sottomisura II.5.2 - progetto ITINERIS" Programme. The authors would like to thank Mr. F. Damiani and Mrs. F. Cecchi.

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