Block-box instrumented toy: a new platform for assessing spatial cognition in infants

F. Taffoni, D. Formica, D. Campolo, F. Keller and E. Guglielmelli

Abstract— This paper describes an interdisciplinary approach to the assessment on infants' behavior, with a focus on the technology. The goal is an objective, quantitative analysis of concurrent maturation of sensory, motor and cognitive abilities in young children, in relation to the achievement of developmental milestones.

An instrumented block-box toy specifically developed to assess the ability to insert objects into holes is presented. The functional specifications are derived from experimental protocols devised by neuroscientists to assess spatial cognition skills.

Technological choices are emphasized with respect to ecological requirements. An ad-hoc calibration procedure is also presented which is suitable to unstructured environments.

Finally, preliminary tests carried out at a local day-care with 12-24 months old infants are presented which prove the in-field usability of the proposed technology.

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 [1]. One of the most challenging applications of NDE is early detection of neuro-developmental disorders such as Autistic Spectrum Disorders (ASD).

Autism is a behavioral 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 fetal development and/or infancy, as demonstrated, for example, by the abnormal pattern of brain growth during late fetal and early postnatal life [2]. Autism is typically diagnosed at the age of 3 years and not earlier than 18 months [3], in many cases after a period of seemingly normal neurological and behavioral development. There is recent evidence that early signs of ASD can be found in infancy, especially in the perceptual and motor domains [4].

Several works proposed to analyze infants motor behaviour by using marker-based stereophotogrammetric systems [5]-[7]. However, the working environment of such systems is highly structured and experimental protocol could become quite obtrusive: for example, in the cited studies infants are seated on a chair, fastened to it, reclined at some degrees with respect to a vertical axis and surrounded by cameras, that is, infants are not in their natural environment. Moreover limbs movements are subjected to line-of-sight issues when marker-based optical systems are employed.

To address these issues a new instrumented toy has been designed to quantitatively assess manipulation tasks of infants without perturbing their natural environment. This work presents the development and the preliminary validation of a sensorized block-box game for ecological behavioral analysis of manipulation tasks in infants.

II. ASSESSING SPATIAL COGNITION

By the end of the first year of life, infants start to pile-up blocks, put lids on cans and insert objects into apertures. Through these activities, the child learns to plan actions that involve more than one item. The ability to solve such problems reflects the childs spatial, perceptual and motor development. In particular, the representational ability to imagine objects in different positions and orientations must be in place before various objects can be fit into apertures.

Recent studies by Ornkloo and von Hofsten [8] show developmental curves, based on statistical rates of success of object-fitting tasks, relative to children aged 14-26 months old.

Specifically, the tasks consisted of inserting cylinders with different cross-sections into a box with similar holes on its lid. All the objects had similar dimensions, 1 mm smaller than the apertures. Different cross-sections were used whose circumference was approximately the same but varied with respect to the number of possibilities they fit into a corresponding aperture.

Based on visual inspection of video recordings, the data analysis consisted (among other things) in assessing horizontal and vertical pre-adjustments. In particular, the outcome was yes/no (i.e. successful or unsuccessful) based on the alignment errors between the object and the box. Both the vertical error (angular misalignment between the longitudinal axis of the object and verticality) and the horizontal error (angular misalignment between the orientations of the cross-section and the aperture) were estimated (from the videos).

The trial was considered unsuccessful for misalignments exceeding 30 deg.

III. BLOCK-BOX PLATFORM

Inspired by such experiments and based on our previous experience with sensorized toys [9], we developed a sensorized core, shown in Fig. 1 (top), for the cylindrical objects with various cross-sections, shown in Fig. 1 (bottom).

In particular, we found that from an *ecological* perspective, the *sourceless* orientation estimation via inertial and magnetic sensors is especially suited to this application. Accelerometers can in fact be used to measure tilt while magnetometers can be used as compass to measure horizontal misalignments. Gyroscopes are required to compensate for non-static effects. Further details on the design can be found in [9] while the filter used to estimate orientation from the sensors raw data is described in [10].
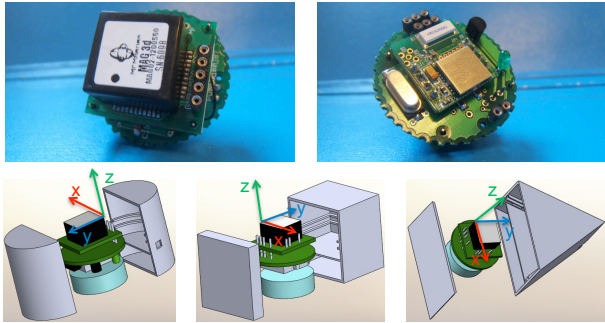

Fig. 1. Kinematics sensing unit (top left). Bluetooth transmitting unit (top right). Examples of assemblies of electronics and batteries for shells with different cross-section (bottom).

Fig. 1 (top) shows the sensing core, mainly consisting of a compact (17.8mm × 17.8mm × 10.2mm), micro-fabricated 9-axis inertial-magnetic sensor (model MAG02-1200S050 from Memsense Inc.). In particular, the device is designed to sense ±2g accelerations, ±1200 deg/sec angular rates, ±1 Gauss magnetic fields, all within a 50 Hz bandwidth. The sensors are coupled with a multi-channel, 12 bits AD converter (model MAX1238 from Maxim Inc.) which can retransmit converted data over a 4-wires I2C bus. For our application, we sample each of the 9 channels at 100 Samples/sec rate. Such data are collected and rearranged in a specific message format by a microcontroller and then retransmitted via a bluetooth device. Finally, two 3.6V Li-Ion Rechargeable batteries (LIR3048 from Powerstream Inc.) are used in series which guarantee approximately an hour of autonomous operation. Data transmitted over the bluetooth interface are collected by a nearby PC, for later data analysis.

IV. IN-FIELD CALIBRATION OF MAGNETO-INERTIAL SENSORS

Magnetometers are meant to sense the geomagnetic field and provide its components $[b_x, b_y, b_z]^T$ along the $\hat{x}$, $\hat{y}$ and $\hat{z}$ axes of the sensing device itself (such axes move with the moving frame). Similarly, the accelerometers are

meant, in static conditions, to read out the components of the gravitational field $[g_x, g_y, g_z]^T$ along the same axes.

Calibration of such sensors is straightforward when one can reliably count on precision alignment procedures, e.g. in a laboratory setting. In [11], a procedure for in-field calibration of magnetometric sensors was presented which does not rely on previous knowledge of magnitude and direction of the geomagnetic field and which does not require accurately predefined orientation sequences. Such a method can be applied to accelerometers as well and is especially suited for clinical applications The procedure relies on the fact the geomagnetic (or gravitational) field has constant components in the fixed frame. As the orientation of the sensors vary, the components in the moving frame also vary but the magnitude of the field keeps constant, i.e. the components are bound to lie on a sphere. Readouts from non-calibrated sensors are therefore bound to lie on an ellipsoid, see [11] for details. Via the least-square method it is possible to robustly estimate the centroid and semi-axes length of the ellipsoid which coincide with the calibration parameters (gain and offsets for each axis).

Based on this method, a calibration protocol was devised to provide a sufficient number of measurements for the algorithm to robustly converge. The instrumented toy (of whatever shape) is secured inside a wooden box, shaped as a parallelepiped, so that the toy does not move as the box is displaced around.

a) Magnetometers:: the box is placed on a table and an approximately 360 deg rotation (no need to be accurate) is performed by keeping one face of the box always parallel and in contact with the table. The same procedure is repeated for four different faces.

b) Accelerometers:: the box is placed on a table and smoothly (i.e. avoiding shocks) tilted by 90 deg along one edge, this is repeated four times[1] until the box returns in the initial position. The whole procedure is repeated with a different initial position.

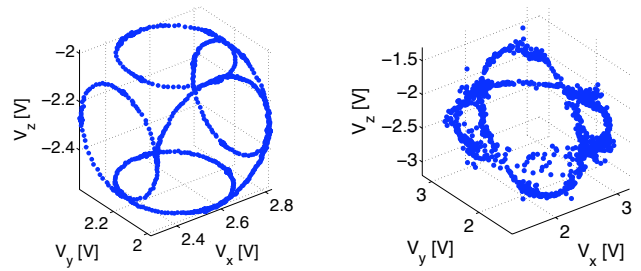*c) Gyroscopes::* the procedure is similar to the one deployed for the accelerometers.

Fig. 2. Plots of the measurements (i.e. voltages V_x, V_y and V_z from the tri-axial sensors) derived from the calibration sequences for the magnetometers (left) and the accelerometers (right).

Measurements derived from a calibration sequence are

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[1]Each time on a different edge: once a 90 deg rotation is performed along one edge, the next edge is the non-consecutive one which also makes contact with the table.

shown in Fig. 2 (left) and Fig. 2 (right), respectively for the magnetometers and for the accelerometers. The least-squares algorithm is then used to derive the best fitting ellipsoids (one for the magnetometers and one for the accelerometers) whose surfaces contain the two sets of measurements.

As previously mentioned, since the geomagnetic field is constant, its components in the moving frame are bound to lie on the calibrating ellipsoid, not only during the calibration sequences but for every possible movement. For this reason, also movements performed during the regular use of the toy, i.e. when the infants plays with it, can be used for updating the calibration parameters, or at least for an on-line check. Similar procedures apply to accelerometers, paying attention to consider only the quasi-static movements, i.e. when accelerations of the movement itself are negligible with respect to gravity. Details about 'in-use' calibration can be found in [12].

V. EXPERIMENTAL RESULTS

The block-box prototype described in Sec. III was tested with several typically-developing children at our local day-care. Representative snapshots from one particular trial are shown in Fig. 3 (bottom) in which the sensorized core was embedded into a cube. In the sequence of snapshots, the child (18 months old) first reaches for the cube with his right hand, than adjusts the orientation of cube with both hands and then successfully inserts the cube into the hole, after some final adjustment and pushing.

In the work of Ornkloo and von Hofsten [8], two video cameras monitored the experiment providing respectively a top and a side view. From the videos, after determining the frame during which the object came into contact with the box, both vertical and horizontal alignment of the object with the aperture were evaluated from the specific frame, with a goniometer. Accuracy of the methods highly depends on the quality of the videos. As stated in the paper, the vertical and horizontal alignments were judged by two coders who disagreed on 31 out of 302 cases.
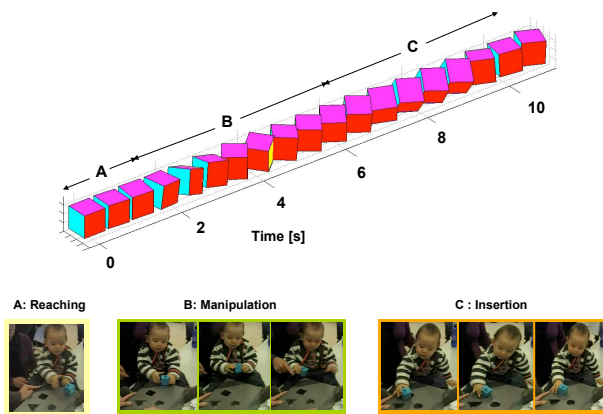

Fig. 3. Experiments with the block-box: reconstructed orientation vs. time (top) and sequence of snapshots (bottom).

In our experiments, the raw data derived from the inertial-magnetic sensors were first fed into a complementary filter

[10] to derive the sequence of orientations of the cube (100 per second, for clarity only few are reported in the top of Fig 3). Once the orientation of the cube is known, the vertical angular error (i.e. tilt with respect to gravity) and the horizontal angular error (i.e. misalignment between the horizontal projection of the cross-section axes of the object and the axes of the aperture) can be determined at any time, as shown in Fig. 4. The time of contact with the box is determined by the peaks of acceleration produced by the shock and distinctively sensed by the accelerometers (2-3 times larger than g).

In Fig. 4, the first 4 seconds are relative to the in-air manipulation of the block. Approximately at time $t = 4s$, the first impact with box occurs (detected by the accelerometers), since at this time both errors are below 30 deg, the pre-adjustment would be considered correct according to [8]. In the remaining 7 seconds, the child tries to insert the cube and only slightly before time $t = 11s$ both vertical and horizontal alignment errors drop to zero and the cube can be successfully inserted. As a final note, the exact time of dropping of the cube can also be determined from the accelerometers because for a body in free fall acceleration always drops to zero.
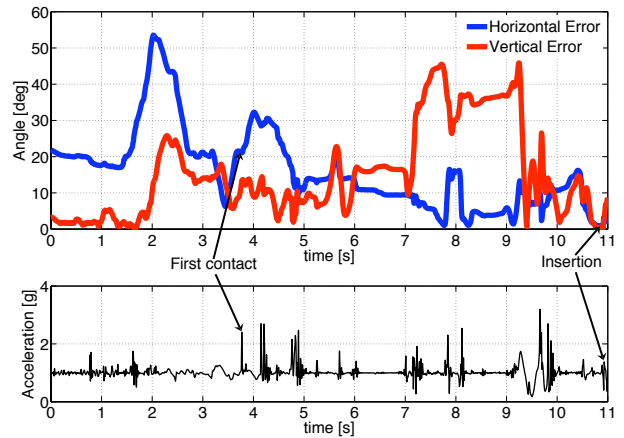

Fig. 4. Typical experimental data with the block-box toy: vertical and horizontal alignment errors (top) and norm of acceleration (bottom).

VI. CONCLUSION

Although developmental milestones of children are largely described in literature, quantitative normative databases of sensorimotor integration skills in relation to increasingly complex tasks are still lacking. On one hand this would extend the current knowledge on developmental mechanisms, with an impact on Developmental Sciences as well as on Robotics. On the other hand, it would allow early diagnosis of neurodevelopmental disorders such as Autism, with a major impact on society.

For this, technology plays a crucial role. Virtually any toy, tool or piece of garment used by children could host all sorts of technology. Our approach is based on a closed loop dialogue between neuroscientists and bioengineers. The

functional specifications for the proposed platforms are derived from experimental protocols devised by neuroscientists. The selection of the technology strictly followed ecological requirements.

In this paper we present a novel instrumented toy, specifically devised to assess the development of spatial cognition in infants.

The scientific focus of this topic is on the ability of a child to mentally rotate an object in order to fit the appropriate hole. The experimental protocol is devised to assess the vertical and horizontal pre-adjustments of the block (with various levels of difficulty in relation to the different cross-sections) at the time of contact with the box. The 'traditional' methods rely on the (time-consuming) manual scoring of videos, frame-by-frame.

The block-box platform embeds magnetic-inertial sensors. The time of contact can be automatically determined from the large acceleration peaks due to the mechanical shock (i.e. when the block hits the box). For that specific time frame vertical and horizontal alignments are also available via the orientation reconstructed from the raw data (e.g. see values in Fig. 4 for $t = 4s$).

In fact, we can reconstruct the orientation *at any time*. Meaning that pre-adjustment kinematics can be assessed during the whole approaching trajectory. The studies of Mari et al. [13] have shown that children with ASD typically have difficulties in activating concurrent motor programs such as reaching for an object and pre- shaping the hand for grasping it. We expect similar findings to hold also for the block-box task, where reaching and pre-adjustment are concurrent motor programs.

In their study, Mari et al. [13] used stereo-photogrammetry, assessing the pre-shaping of the hand via reflective markers on the index finger and the thumb. Although valuable for research, such a method is hardly applicable to clinical practice for screening purposes. The block-box platform is suitable to work in day-cares, or in the office of a pediatrician. In this way a large number of children may actually be objectively monitored.

REFERENCES

[1] D. Campolo, F. Taffoni, G. Schiavone, C. Laschi, F. Keller, E. Guglielmelli, A Novel Technological Approach Towards the Early Diagnosis of Neurodevelopmental Disorders, *30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Vancouver, Canada, 2008, pp 4875-4878.

[2] F. Keller, A. M. Persico, The neurobiological context of autism, *Mol. Neurobiol.*, vol 28, 2003, pp 1-22

[3] S. Baron-Cohen, S. Wheelwright, A. Cox, G. Baird, T. Charman, J. Swettenham, A. Drew, P.Doehring, Early identification of autism by the CHecklist for Autism in Toddlers (CHAT), *J. R. Soc. Med.* vol 93(10), 2000, pp 521-525.

[4] P. Teitelbaum, O. Teitelbaum, J. Nye, J. Fryman, R. G. Maurer, Movement analysis in infancy may be useful for early diagnosis of autism, *Proc. Natl. Acad. Sci. USA* vol 95, 1998, pp 13982-13987.

[5] C. von Hofsten, L. Ronquist, The Structuring of Neonatal Arm Movements, *Child Dev.*, vol 64, 1993, pp. 1046-1057.

[6] A. N. Bhat, J. H. Heathcock, J. C. Galloway, Toy-oriented changes in hand and joint kinematics during the emergence of purposeful reaching, *Infant Behav. Dev.*, vol 28, 2005, pp 445465.

[7] A. N. Bhat, J. C. Galloway, Toy-oriented changes during early harm movements: Hand Kinematics, *Infant Behav. Dev.*, vol 29, 2006, pp 358-372.

[8] H. Ornkloo, C. von Hofsten, Fitting objects into holes: on the development of spatial cognition skills, *Dev. Psychol.* vol 43, 2007, pp 404-16.

[9] D. Campolo, E. S. Maini, F. Patanè, C. Laschi, P. Dario, F. Keller, E. Guglielmelli, Design of a Sensorized Ball for Ecological Behavioral Analysis of Infants, *IEEE International Conference on Robotics and Automation (ICRA)*, Pasadena, California, USA, 2007, pp. 1529-1534.

[10] D. Campolo, L. Schenato, L. J. Pi, X. Deng, E. Guglielmelli, Multimodal Sensor Fusion for Attitude Estimation of Micromechanical Flying Insects: a Geometric Approach, *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2008, pp 3859-3864.

[11] D. Campolo, M. Fabris, G. Cavallo, D. Accoto, F. Keller, E. Guglielmelli, A Novel Procedure for In-field Calibration of Sourceless Inertial/Magnetic Orientation Tracking Wearable Devices, *the first IEEE / RAS-EMBS Intl Conf. on Biomedical Robotics and Biomechatronics (BIOROB)*, Pisa, Italy, 2006, pp 471-476.

[12] J.C. Lotters, J. Schipper, P. H. Veltink, W. Olthuis, P. Bergveld, Procedure for in-use calibration of triaxial accelerometers in medical applications, *Sens. Actuators A Phys.* , vol 68, 1998, pp 221-228.

[13] M. Mari, U. Castiello, D. Marks, C. Marraffa, M. Prior, The reach-to-grasp movement in children with autism spectrum disorder, *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, vol 358, 2003, pp 393-403.