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CONSIDERATIONS REGARDING THE USE OF SENSORS BY SELF-RECONFIGURABLE ROBOTS

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ABSTRACT
The first section of the paper presents an approach of sensor types, usually used by self-reconfigurable robots modules, and their roles. Main restrictions in implementing sensors to different modules are revealed. The second section of the paper is dedicated to the use of acceleration sensors, very efficient due to their MEMS technology and the variety of information offered to the control system, regarding: accelerations, collisions, gravity, vibrations, orientation etc. Orientation matrices and corresponding orientation angles are derived and some qualitative deductions, based on certain signal thresholds and comparisons are introduced.
Keywords: Reconfigurable Mobile Robots, Acceleration Sensors, Orientation Matrices

1. INTRODUCTION
Sensor systems play an important role in assuring the functions of mobile self-reconfigurable robots, both for measuring the current states of every particular module (internal sensors), as well as, for searching and investigating the surrounding environment (external sensors).

1.1. Sensor types used and their roles
The main role of internal sensors is to measure the positions and displacements in the cinematic joints, which ensure the degrees of freedom of a module, but also to measure accelerations. External sensors have some important roles for: determination of positions and orientations of coupling faces of the modules for docking operations; selection of the adequate locomotion mode; identification of obstacles in the environment, for collision avoiding; start of a certain behaviour, as response to different ground conditions etc.

In spite of these very important roles, the endowment of existing self-reconfigurable robots with sensor systems seems to be rather poor [2]. The author analyses the characteristics of the main self-reconfigurable robotic systems from different points of view, including the sensors used. Some robots don't have sensors, other use sensors, mainly, for joint position and docking aids. On a scale from 1 to 3, where 1 is worst and 3 is best, all sensor systems are noted with 1. A logic question is: why such a reduced number of sensors, although they are important in improving robots functions? This question assumes, at least, two decent answers:

- Modules of self-reconfigurable robots have small dimensions, in the range of millimetres or centimetres, and, within that little volume, mechanical elements, power sources, processor board, actuators, sensors, communication modules etc. must be integrated. Space restrictions severely reduce the sensors number.
- A hardware and software compatibility and integration must be achieved between the control processor and different sensor systems, a very difficult task, due to the variety of differentsensor

types. On the other hand, the use of more complex sensors increases the computation time and exceeds, in many cases, the processors capacity to work in real time.

1.2 Considerations about heterogeneity or homogeneity of modules

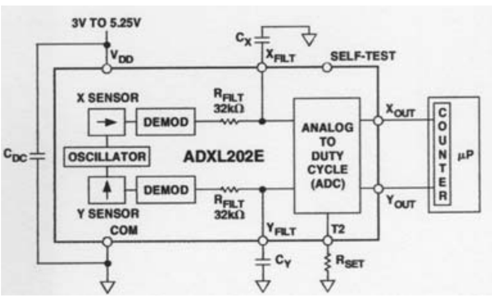
Endowment with sensors is often the main criterion in deciding about heterogeneity or homogeneity of self-reconfigurable robots modules. In [1] some interesting conclusions are derived, regarding this issue:

- In the last years a tendency of designing and developing modules with a certain degree of heterogeneity can be put in evidence, mainly because it is not efficient to equip all modules with more complex sensors. Modules can be homogeneous in respect with their actuators, but heterogeneous from the point of view of endowment with sensors. It is also difficult to develop solely distributed algorithms for planning all activities of the modular robotic system, and, therefore, one or more modules must be able to perform a centralized planning. One pertinent solution implies the design of a co-ordinator module, equipped with more complex sensor systems and able to decide a global strategy, while the other modules have distributed algorithms, for a lower planning level, based on local information, received from less complex internal or external sensors. The localization solution detailed in [4] is based on this solution.
- Taking into account the dimensions of robots modules, two groups can be distinguished: "macro-modules, with sizes between 3 cm and 26,5 cm, manufactured with classical manufacturing and assembly technologies and including all actual existing self-reconfigurable robots; "micro-modules", with sizes less than a centimetre, manufactured with MEMS technologies. MEMS is the integration of mechanical elements, sensors, actuators and electronics on a common silicon substrate, through micro-fabrication technologies. In the second section of this paper a macro-module is considered, but equipped with a MEMS sensor.

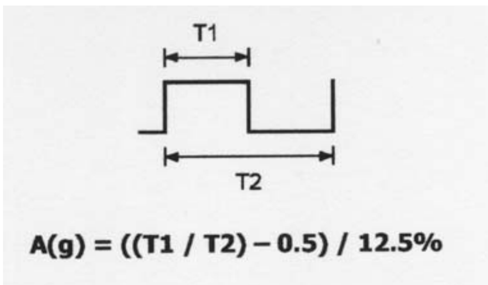
2. ACCELERATION SENSORS

2.1 Role; Working principles

Signals from acceleration sensors can be used by the module's control processor in order to determine: position of each side with respect to the axis of gravity; movement or lack of movement; tilt angles with respect to different axes; shocks and collisions etc.



a)



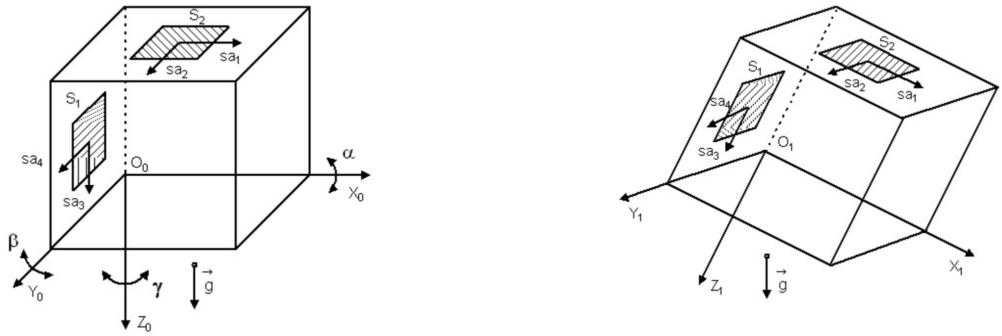
b)

Figure 1. ADXL202E: a) Block diagram; b) Output signal

Two types of dual-axis (X-Y) acceleration sensors, both in MEMS technology, will be briefly described.

The first sensor, Memsic 2125 (Parallax Inc.), contains, internally, a small heater. This heater warms a "bubble" of air within the device. When gravitational forces act on the bubble, it moves and this movement is detected by very sensitive thermopiles (temperature sensors). On-board electronics convert the bubble position (relative to g-forces) into pulse outputs for the X and Y axes. The second sensor, ADXL202E (Analog Devices), is a surface micro-machined polysilicon structure built on the top of a silicon wafer. Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces. Deflection of the structure is measured using a differential capacitor that consists of independent fixed plates and central plates attached to the moving mass. The fixed plates are driven by 180° out of phase square waves. An acceleration will deflect the beam and unbalance the differential capacitor, resulting in an output square wave whose amplitude is proportional to acceleration (fig.1, b). Phase sensitive demodulation techniques are then used to rectify the signal and determine the direction of acceleration. Due to their same duty cycle output and same type of connector , the two sensors are fully compatible. Connection to a processor requires just two I/O pins.

2.2 Module used for experiments



a) b)

Figure 2. Module equipped with two 2-axis acceleration sensors

The module used for experiments is a simple cube with two, 2-axis Memsic 2125 acceleration sensors, mounted on adjacent faces (fig.2). No moving facilities were used, just different static positions of the cube. Each sensor can measure 0 to ±2g on either axis, with less than 1 mg resolution. The pulse outputs are set to a 50% duty cycle at 0 g. The duty cycle changes in proportion to acceleration and g force can be calculated with a suitable formula (fig.1, b). Since there are two sensors, S_1 and S_2, and each of them can measure accelerations along two axes, signals sa2 and sa4 are redundant. This redundancy can be useful in certain conditions, but only accelerations measured by sa1, sa2 and sa3 have been considered, which are parallel to the axes of the co-ordinate system, $O_1x_1y_1z_1$, attached to the cube. Initially this system is coincident with a reference system, $O_0x_0y_0z_0$, with z_0 axis along the gravity vector **g** (fig.2,a). Thus, the initial orientation matrix of sa1, sa2 and sa3 is the 3x3 unit matrix. The only force seized by both sensors is gravity and the last raw of the unit matrix, with elements proportional with projections of sa1,sa2 and sa3 upon z_0 (**g**) axis, indicates that only sa3 is influenced.

2.3 Rotation matrices; Tilt angles

The cube is rotated, with a certain angle: α, with respect to x_0, β, with respect to y_0 or γ with respect to z_0. Corresponding rotation matrices are:

$$Rot(x_0,\alpha)=\begin{bmatrix}1 & 0 & 0\\ 0 & c\alpha & -s\alpha\\ 0 & s\alpha & c\alpha\end{bmatrix};\quad Rot(y_0,\beta)=\begin{bmatrix}c\beta & 0 & s\beta\\ 0 & 1 & 0\\ -s\beta & 0 & c\beta\end{bmatrix};\quad Rot(z_0,\gamma)=\begin{bmatrix}c\gamma & -s\gamma & 0\\ s\gamma & c\gamma & 0\\ 0 & 0 & 1\end{bmatrix}.\quad \ldots(1)$$

$s\alpha$ and $c\alpha$ have been used for sine and cosine of α. Matrices (1) indicate that a rotation along z_0 axis does not change the sensor signals, but a rotation with respect to x_0 or y_0 axes transfers a part of gravity from sa3 to sa2, respectively, to sa1. Some conclusions can be derived examining matrices (1):

- If two of the signals sa1, sa2, sa3 are zero or very close to zero (under a certain threshold), then the cube lies horizontally, on that face whose normal is along sa1, sa2, respectively sa3.
- If one of the signals sa1, sa2, sa3 is zero or very close to zero (under a certain threshold) and the other two signals are greater than zero (over a certain threshold), than the cube is rotated, with a

certain angle, along the axis with a zero signal. This angle can be calculated from matrices (1) with simple arctg functions.

If the cube is rotated, successively, along two of x_0, y_0, z_0 axes, the configuration of rotation matrix is more complex and depends, due to the fact that matrix multiplication is not commutative, on the order in which rotations are performed. Assuming a rotation with angle α along x_0 axis, followed by a rotation with angle β along y_0 axis, the corresponding rotation matrix will be:

$$Rot(x_0,\alpha;y_0,\beta)=\begin{bmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{bmatrix}\bullet\begin{bmatrix} 1 & 0 & 0 \\ 0 & c\alpha & -s\alpha \\ 0 & s\alpha & c\alpha \end{bmatrix}=\begin{bmatrix} c\beta & s\beta.s\alpha & s\beta.c\alpha \\ 0 & c\alpha & -s\alpha \\ -s\beta & c\beta.s\alpha & c\beta.c\alpha \end{bmatrix}, \qquad \ldots(2)$$

which differs from a rotation matrix which assumes that rotation along y_0 axis is carried out first.

If the cube is subject, successively, to rotations with respect to all 3 axis, there are six possibilities for the order of these rotations and six corresponding rotation matrices. For example, the rotation matrix for a rotation with α along x_0, followed by angle β along y_0 and, than, γ along z_0, has the configuration:

$$\begin{bmatrix} c\beta.c\gamma & s\alpha.s\beta.c\gamma-c\alpha.s\gamma & c\alpha.s\beta.c\gamma+s\alpha.s\gamma \\ c\beta.s\gamma & s\alpha.s\beta.s\gamma+c\alpha.c\gamma & c\alpha.s\beta.s\gamma-s\alpha.c\gamma \\ -s\beta & s\alpha.c\beta & c\alpha.c\beta \end{bmatrix}. \qquad \ldots(3)$$

Indubitable, equations (2) and (3) can serve for calculating angles α and β. In [3] equation (3) is used for calculating the orientation angles of the modules of a PolyBot robot, with:

$$\alpha = \tan^{-1}(sa2/sa3) \text{ and } \beta = \sin^{-1}(-sa1). \qquad \ldots(4)$$

In this sense the order of rotations must be known and memorized by the module's control processor. In many cases this is not possible, especially when the module is subject to inclinations, while moving on a rough terrain. Based on these considerations, some thresholds will be established for each of the 3 signals from sensors and the module's control system will reason in the following manner:

- If two signals are under the "zero threshold", the cube lies horizontally and the corresponding support face can be identified;
- If one signal is under the "zero threshold", the cube is rotated with respect to one of the non-vertical axes with a certain angle, which can be calculated using equation (3). If an upper threshold is exceeded, the control system must react to keep the module in a stable position.
- If all three signals are over the "zero threshold", the cube is rotated with respect to two or three axes. If the sequence of these rotations is known, tilt angles can be calculated using equations similar to (3). In any case, if upper thresholds are exceeded, the control system must react to keep the module in a stable position.

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