E-field Sensors and Sensor-based Control Strategies for M/M Safe Cooperation

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Abstract — In this paper we describe the use of an artificial sensitive skin, realized by means of E-field sensors, for enhancing safety and man machine cooperation in robotic work-cells. Sensory signal from the sensitive skin are interpreted with the aid of additional information about the robot’s motion, so to provide emergency stop signal in case of unintentional proximity or contact between man and robot or, alternatively, in case of intentional contact by the man, to transmit suitable commands. An experimental prototypical installation on an industrial manipulator is described and results of various tests are illustrated.

I. INTRODUCTION

Industrial robots are commonly used in a variety of applications, where they offer economic advantages, as well as increment of productivity and quality, thanks to higher flexibility, versatility and dexterity with respect to other automated machines. In standard industrial installations, specific measures are taken to keep workers out of the robots workspace during operations. In this way, the risk of accidents is reduced and safety is assured, but, at the same time, the possibility of profitable, strict cooperation between man and robot is largely prevented.

New rules for the installation and use of automatic machines and recent technological improvements can provide tools and ways to change the above described situation. On one hand, advances in automation and artificial intelligence can be exploited to improve the situation awareness and the decision capability of robots, so to make possible, to some extent, a safe interaction with humans in a shared workspace. On the other hand, rules to assure safety in industrial robotic installations are currently under revision by the Technical Committee ISO/TC 184-SC2 “Robots and robotic devices” and publication of a new version [1, 2] of the international standards will be completed in 2011. In particular, new standards aim at establishing requirements for a safe, strict cooperation, in a common workspace, between man and robot through the characterization and classification of possible dangerous situations and through the definition of feasible preventive measures, on the basis of the general principles expressed in [2].

In this framework, a key factor in facilitating cooperation between man and robot is represented by sensory systems that can give to the robot a clear, rich perception of its environment, so to regulate its behavior accordingly.

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An attempt to create a methodology based on the analysis of risks and dangers for designing safe, man centered robotic work-cells has been made in [3]. In [4], possibly dangerous contacts between man and robot have been dealt with by proposing a notion of Safe Space, based on the pain’s human tolerance. In [5], interaction between man and robot has been regulated by controlling the distance between them, using high precision sensory systems, consisting of many sensors that detect people and monitor movements. Another possible approach consists in equipping the robot with an artificial sensitive skin which may serve as touch sensory system and detect any contact that may cause risks or dangers (see [6]). Artificial skins may be constructed by integrating a large number of sensing devices, such as pressure sensors and temperature sensors, in a sheet-like, flexible structure (see [7, 8, 9, 10]).

In a previous work [11], the authors proposed the use of a low cost, versatile sensory system based on sensors of electric field (E-field sensors) for the realization of human/robotic work-cell. The sensing elements in such system are electrodes that can be shaped and assembled to cover robot links as an artificial, full body, sensitive skin (see [6]). The system is able to act as a distributed touch sensor and also as a distributed proximity sensors. Installation and operational tests performed on a reduced scale model of an anthropomorphic robotic arm gave satisfactory results (see [11]). A possible use of capacitive sensors in industrial application, similar to the above one, was described in [12, 13], limiting the functionality of the system to obstacle detection and avoidance.

Here, continuing in the same line of [11], we illustrate the implementation of (components of) the sensory system on a 6 DOF anthropomorphic robotic arm Comau SmartSix® and the results of a series of tests. Then, we present a new, innovative modality for achieving cooperation between man and robot that, exploiting the basic features of the sensory system, is able to assure safety and to facilitate the man/machine communication in accordance with the new ISO standards in a shared workspace.

Conceptually, the way in which the sensory signal is used in our approach is similar to that described in [8] (see also [14, 15]), made more effective and simpler by exploiting additional information that is available in the considered industrial application. The basic idea is to develop a control strategy by endowing the system with the ability to distinguish between intentional contacts and unintentional ones. This is done in a simple, very effective
way by exploiting additional, available information about the current state of the robot. In practice, contact with (or proximity to) a generic component of the sensitive skin during the robot motion is interpreted as unintentional and it gives rise to an emergency stop command. On the other hand, contact with a (selected) component of the sensitive skin while the robot is not moving is interpreted as intentional and (depending on which component is touched) it represents a suitable input command. By organizing the coordinated work of man and robot as a sequence of phases, during which the robot is either moving or waiting for instructions from the operator, it is possible to realize work-cells in which man and robot can share safely the workspace, simple instructions can be easily transmitted from the first to the second and a profitable synergy between the robot’s strength, speed or precision and the man’s superior decisional capability can be actuated.

The paper is organized as follows. In Section II we discuss characteristics, features and realization technology of the E-field sensors that are the basic elements of the sensory system and their integration into an artificial, sensitive skin. In Section III, we first describe, in general terms, how to calibrate and use the artificial skin. Then, we illustrate the sensor based control strategy that can be developed by exploiting the sensory information acquired by the artificial skin. In Section IV, we describe a prototypal installation on an anthropomorphic manipulator and the results obtained in a series of experiments. The cooperation modality based on the sensory system’s features is then illustrated together with the results of further tests.

II. E-FIELD AND SENSITIVE SKIN

The use of E-field sensors in robotics has been considered, in particular, in [16, 17], where interesting applications of E-field imaging and related results are described. In constructing the sensors we employ, we partially apply the technique described [16].

From a general point of view, E-field sensors are capacitance sensors that work by generating an electric field in the surrounding environment and by detecting the variation of capacitance induced by objects that interfere with the field. Their measuring capabilities are limited to objects whose dielectric properties differ from those of the medium which fills the space occupied by the electric field. This makes human beings very good candidates for e-field imaging in their environment, because, having a high content of water, the human body has a dielectric constant largely different from that of the air.

The capacitive sensor we use to build the sensitive skin is based on the Theremin technology, developed in 1919 by the physicist Leon Theremin to realize the first electronic musical instrument, which took his name (see [18]). An application along these lines has been studied and developed in [16, 17], where a capacitive sensor for a robotic hand has been developed.

A. Theremin sensor

Theremin sensors for proximity and touch can be constructed in a simple and inexpensive way. A sensing oscillator is connected with an electrode, of any shape, which acts as antenna to generate the electric field in the surrounding environment and a second, reference oscillator is connected with a stable capacitor. Using a trimmer, in a tuning phase, the frequency of the reference oscillator is set, in our implementation, at 1.8MHz and that of the other oscillator is set at a slightly different value, so that, combining the output of the two oscillators by a frequency difference circuit, we get a signal whose order of magnitude is 0.1MHz. If the capacitance of the electrode is modified by the presence of a nearby object that interferes with the generated electric field, the sensed frequency varies and so does the output of the frequency difference circuit. Experiments show that, in the situation better described below, variations occur in a range going from about 0.5kHz, when a human operator approaches at a distance of 0.05m from the electrode, to about 0.1MHz, when the operator touches the electrode. Processing the output of the frequency difference circuit by means of a CMOS counter, we divide the frequency by 1024, so that its value can be possibly acquired by means of a low cost 8-bit microcontroller.

Complex apparatus, consisting of several theremin sensors, can be constructed in such a way that individual electrodes form portions of an artificial, sensitive skin used to cover a manipulator link. In the experimental installation we developed, two electrodes, consisting of a thin conductive plate of, respectively, about 400cm² and 100cm², have been placed on the links of a 6 DOF anthropomorphic robotic arm Comau SmartSix® as shown in Figure 1 (compare with the installation on the reduced scale model described in [11]).

During normal operation, the electric brushless motors of the robot generate an electromagnetic disturbance, in terms of mean value and standard deviation of the acquired signal, on the waves generated by the sensors’ oscillators. In addition, the mass of the robot softens the effects due to the presence of a nearby object having mass and dielectric constant similar to those of a human body. Keeping the robot’s motors braked in a generic configuration, the response of the sensor on the last link is shown in Figure 2. The default frequency of the difference circuit has been set, by the trimmer, at about 110KHz and the graph in the upper part of Figure 2 shows the effect of a human operator approaching at 0.05m from the electrode at time 300s and remaining there for 10s. Frequency’s variation shown in the graph is, in this case, of about 0.5Hz (recall that the signal coming from the frequency difference circuit is divided by 1024). The graph in the lower part of Figure 2 shows the effect of a human operator touching the
electrode at time 210s. In this case, the resulting variation in the graph is of about 150Hz.

Repeated tests of this kind prove that the considered sensor is able to detect proximity and contact between the robot’s link and man. It is clear that, by limiting to a suitable maximum value the robot’s speed, the ability to detect proximity with man at 0.05m gives sufficient time for stopping the robot’s motion before colliding. The maximum allowed value of speed, which depends on the robot’s characteristics and on the modalities of use, can be evaluated experimentally. The sensor makes possible, in this way, to share the workspace between man and robot by respecting the principle of a safe interaction in accordance with the general principles of [1, 2].

B. Artificial skin

In realizing an artificial skin consisting of several theremin sensors, the only technological problem is given by the necessity of performing a fast, on-line processing of the signals. As mentioned above, in order to simplify the experimental activity, only two theremin sensors have been installed on the 6DOF anthropomorphic robotic arm Comau SmartSix, although the architecture of the sensitive skin we designed may include more. The sensor’s control electronics consists of custom made modular elements, called Signal Generation and Management Card (SGMC). Each SGCM drives up to four electrodes, using a single reference oscillator (LM555) and four sensing oscillators, one for each electrode. Trimmers that regulate the RC factor are used for calibration. Frequency comparison is performed by CMOS flip-flops and the resulting differences are divided by 1024 by ripple counters. The four output signals coming from each SGMC are acquired, and the normal operating phase, is closer to the actual one and, then, it compares the actual sensory signals with the default values associated to that position. In this way, the processing unit detects possible deviations from the default values, which are to be interpreted as occurrences of proximity or contact.

In order to implement the above described modality, two different phases have to be considered: a Calibration Phase, in which the default values for the configuration of the discretization are acquired, and the normal Operating Phase, in which the sensory signals, the information about motion and the recorded default values are used to detect proximity or contact. The calibration phase can be performed off-line and, in principle, it does not require a high computational power that, conversely, is crucial in the normal operating phase.

A. Calibration phase

In order to start the Calibration Phase, it is first necessary to choose a discretization of the workspace. To do this, it is convenient to refer to the robot’s joint space and to proceed by discretizing the range of each joint variable. In this way, default values for the electrodes’ signal can be collected in a unambiguous manner and associated both to the control variable used to govern the robot’s behavior and to configurations that can be easily computed by means of direct cinematic.

After choosing the discretization step(s), by direct measuring, one can form a Calibration Table like that described (in the case of \( j \) independent joint variables and \( k \) electrodes in the artificial skin) in Table I: (\( \theta_{i1}, \ldots, \theta_{i2} \)) represent a point in the discretized workspace and (\( F_{i1}, \ldots, F_{i2} \)) represent the default signals of the various electrodes in the corresponding robot’s configuration and additional data, if desired, can be included. In practice, joint variables are sequentially and cyclically increased by the
discretization step and, at each stage of that process, the value of each electrode’s signal is evaluated and recorded in the Calibration Table.

The Calibration Phase takes a time that depends on the number of joint variables, on the dimension of the workspace, on the discretization steps and on the signal acquisition procedure. Calibration is done automatically by programming the robot to take all the configurations that discretize the working space. After reaching each configuration, the robot stops, its control units communicate to the processing unit of the sensitive skin the values of the joint variables that identify the present configuration and the processing unit evaluate the default value of the electrodes’ signals (possibly by averaging and filtering several measurements). After completing the evaluation, the processing unit records the data in the Calibration Table and it sends a signal to the robot’s control unit in order to move to the next configuration. Figure 3 and 4 show the behavior of the sensory signal during a Calibration Phase.

B. Operating phase

The Operating Phase is organized in such a way that, during it, man and robot can share the same workspace in safety conditions and in such a way that the man can give instructions, in a simple and direct way, to the robot at designated times, so to govern its future behavior by choosing between two or more alternatives. In the Operating Phase, the robot is governed by its controller in order to perform a set of scheduled operations and information about the current joint positions is sent to the processing unit of the sensitive skin at a fast (in comparison to the maximum robot speed in the operating phase) rate. Operations performed by the robot are described by a set of primitives that include (sequences of) motions and waiting phases. Waiting phases are intended to give to the man the possibility to input commands, as described below, which specify the next operation. Electrodes’ signals are acquired and, using the information on the current joint positions and the Calibration Table, they are compared by the processing unit of the sensitive skin with the default values corresponding to the closest recorded position. In case of deviation, according to its entity and to a given set of thresholds, the processing unit detects proximity or contact between an object or part of an operator’s body and one of the electrodes.

The processing unit is able to distinguish between motion and waiting phase by analyzing the time behavior of the joint variables over a short (in comparison to the maximum robot speed in the operating phase) period of time and, according to this, it interprets proximity or contact as unintentional (during the motions) and as intentional (during the waiting phases). Different output signals are then synthesized, according to the unintentional or intentional character of the occurrence and to the specific interested electrode, and they are sent by the processing unit to the robot controller via serial link. In case of unintentional occurrence (proximity or contact during motion), the synthesized signal is an emergency stop signal, which prevents the robot by colliding or limits the effects of collision. In case of intentional occurrence (proximity or contact during the waiting phase), a different signal for each interested electrode can be generated. Therefore, the man, by touching a specific electrode or a combination of them during the waiting phase, can communicate a specific command to the robot. Commands can, in turn, be associated to specific (set of) primitives and, therefore, they can be used to indicate the next operation to be performed.

IV. AN EXAMPLE OF INSTALLATION AND USE

As already mentioned, an artificial skin, consisting by two electrodes and a CompactRIO processing unit, has been installed on a 6 DOF anthropomorphic robotic arm Comau SmartSix, equipped with Comau C4G controller. The workspace of the robot has been limited by keeping equal to 0 the values of the wrist joint variables $\theta_4$, $\theta_5$, $\theta_6$ and by imposing the following ranges on the remaining ones (see Figure 1): $5^\circ \leq \theta_1 \leq 180^\circ$; $0^\circ \leq \theta_2 \leq 80^\circ$; $f(\theta_3) \leq \theta_3 \leq 0^\circ$; where $f(\theta_3)$ has been chosen in such a way to prevent the robot wrist to collide with the ground ($\text{min} f(\theta_3) = -125$).

Together with the choice of using only two electrodes, work space limitations are motivated by the interest in simplifying, in the present phase of study, experiments and data collection. Adding more electrodes, up to additional 30 ones, and removing the work space limitations will increase the computational burden and require more practical work.

The workspace has been discretized by a step of $5^\circ$ for all three joint variables, for a total of about 5000 configurations. In general, the discretization step has to be chosen according to the characteristics of the realized sensor. As mentioned in Section II.A, our sensor can detect proximity of an operator at 0.05m, which, on the average, is about half the distance between the position of the center of the robot’s wrist in any one of the considered configurations and the position of the center of the robot’s wrist in the closest one in the Cartesian space.

The two electrodes have been placed, respectively on the first link (electrode 1) and on the second link (electrode 2) of the robot as shown in Figure 1. Electrodes are realized by means of a thin aluminum plate, placed around the second link and on one side only of the first link. Of course, different shapes and locations are possible. The total area of the electrode on the second link is about 400cm$^2$ and the total area of the electrode on the first link is about 100cm$^2$.

In order to derive the calibration table, the robot has been programmed to assume sequentially all the configurations which discretize the workspace and to stop
in each configuration to let the processing unit of the sensitive skin to collect data. In each configuration, 100 measurements for each electrode have been taken, waiting 5ms between each measurement and the following one. In order to avoid the presence of trends, due to the accumulation of electric charges on the electrodes, between two consecutive measurements, electrodes are periodically grounded by acting on a dedicated circuit. Measurements are averaged and the resulting value is associated as default value to the configuration at issue. Time spent in each configuration is 1.1s, due to the interval between consecutive measurements and data exchange between the robot controller and the processing unit through the serial connection. In the calibration phase, configurations vary with time and the graph of Figure 3 shows the difference between the reference frequency and the sensed frequency of electrode 1 (divided by 1024) in the various configurations, as the configuration proceeds over time (the default frequency of the difference circuit was set, by the trimmer, at about 205KHz). Variability is due to the influence of the robot mass and of the other electrode on the generated electric field and, as expected, it presents a cyclic behavior, due to the fact that joint variables are incremented in nested cycles. Figure 4 shows an enlargement of the same graph where cyclic behavior, as the robot assumes similar configuration, is evident.

The Calibration Table has the form described in Table I, with $j = 3$ and $k = 2$, where $\theta_{i1}$, $\theta_{i2}$, $\theta_{i3}$ are the values of the joint variables in the i-th configuration, $F_{i1}$ and $F_{i2}$ are the differences between the reference frequency and the sensed frequency of electrode 1 and of electrode 2 (divided by 1024) and the only additional datum is the time $T_i$ at which the i-th configuration is assumed. After the Calibration Table has been obtained, the system consisting of the robot and of the artificial sensitive skin is ready to operate.

During the Operating Phase, the speed of the robot has been limited to $\frac{3}{4}$ of its maximum speed. Experiments have shown that, on the average, the space covered by the robot’s wrist at $\frac{3}{4}$ of the maximum speed before stopping after an emergency stop command has been given is less than 0.05m, that is: it is smaller than the distance at which the presence of the operator is detected by the sensor. This means that safety requirements, in the line of [1, 2] are respected.

A set of experiments have been carried on in order to test the performances of the system during the Operating Phase. The behavior of the robot can be represented, in general terms, as a sequence of transitions between generalized states, which are characterized by a (set of) specific action(s), that are activated by the occurrence of given events, as illustrated in Figure 5. Referring to the Figure, states indicated by $M \#$ correspond to a condition in which the robot performs a given motion. Events indicated by Unintentional Contact represent situations in which proximity or contact is detected during motion. State indicated by $S$ corresponds to a condition of emergency stop, caused by the occurrence of unintentional proximity or contact during the motion. States indicated by $W \#$ correspond to a waiting phase, which is a condition in which the robot, having completed part of its task, waits for instruction on how to proceed by the operator. Events indicated by Intentional Contact $\#$ represent situations in which contact has been detected on the electrode $\#$ during a Waiting Phase. By generating such events, the operator causes transition to the desired next state.

In the simple Operating Phase implemented in the experiments only three state $M_1$, $M_2$, $M_3$ and two possibility of intentional contact $IC_1$ and $IC_2$ have been considered:

- state $M_1$ consists in picking a small objet from a table, in moving and holding it in a position where it can be inspected by the operator,
- state $M_2$ and state $M_3$ consist, respectively, in placing the object in place A or place B, depending on the decision of the operator, signaled by touching electrode 1 ($IC_1$) or 2 ($IC_2$).

The pick-hold-place task was repeated a number of time, while information about the current values of the joint variables was sent by the robot’s controller to the artificial skin processing unit every 0.1s. The tests performed have shown the desired behavior of the system, which has accomplished its tasks, stopping in case of unintentional contact and actuating the command transmitted by means of intentional contact.

V. CONCLUSION

The construction of an artificial skin sensory system by means of E-field sensors and its use in the development and implementation of a strategy for safe cooperation between man and robot in a work-cell have been described. Functional tests show the feasibility of an efficient, sensor based control strategy that employs the features of the sensory systems both for guaranteeing safety and for facilitating communication and cooperation. Further issues that need to be taken into account are related to the augment of complexity and computational burden that arise when installing additional sensors. In applications which require small end effectors and/or concern the manipulation of small objects, the wrist DOFs can be neglected, to avoid increasing the number of configurations to be considered in the Calibration Phase. Alternatively, the possibility to compute default values from a model of the system can be considered. Finally, the effect of electrostatic discharges and other electromagnetic interferences in industrial environments has to be investigated.

REFERENCES


### TABLE 1 - CALIBRATION TABLE

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<td>$F_{m1}$ $F_{m2}$ ... $F_{mk}$</td>
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Figure 1. Sensor’s response (electrode on the last link in Figure 3):
- human operator approaching at 0.05m from the electrode at time 300s and remaining there for 10s;
- human operator touching the electrode at time 210s.

Figure 2. Electrodes’ location (in red) on the Comau SmartSix.

Figure 3. Difference between the reference frequency and the sensed frequency of electrode 1 (divided by 1024) in the various configurations, during calibration (default frequency = 205KHz).

Figure 4. Enlargement of Figure 6.

Figure 5. Sequence of operations in the Operating Phase.