Distributed discrete state acquisition and concurrent pattern recognition in a MEMS-based smart surface

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***Abstract*—A distributed smart surface based on MEMS technologies is considered. We lay down the mathematical foundations of distributed discrete state acquisition. Distributed state acquisition algorithms and concurrent pattern recognition methods are proposed. A multithreaded Java smart surface simulator which runs on multicore machines is presented. A first series of computational results is displayed and analyzed.**

Keywords—MEMS; smart surface; state acquisition; pattern recognition; distributed algorithms; asynchronous algorithms; communication management; multithreading; multicores

I. INTRODUCTION

Micro-Electro Mechanical Systems (MEMS) actuator arrays with embedded intelligence, which are often referred to as smart surfaces, have gained attention recently, e.g. see [1] and [2].

We consider here a smart surface designed for conveying positioning or sorting micro parts (see [4] and [5]). The MEMS-based distributed micro robotics system is an array of fully integrated micro modules, the so-called cells. Each cell contains sensor, processing unit and actuator (see [3] and [4]). Cells are connected via a communication network. Each cell has at most 4 neighbors (see Fig. 1).

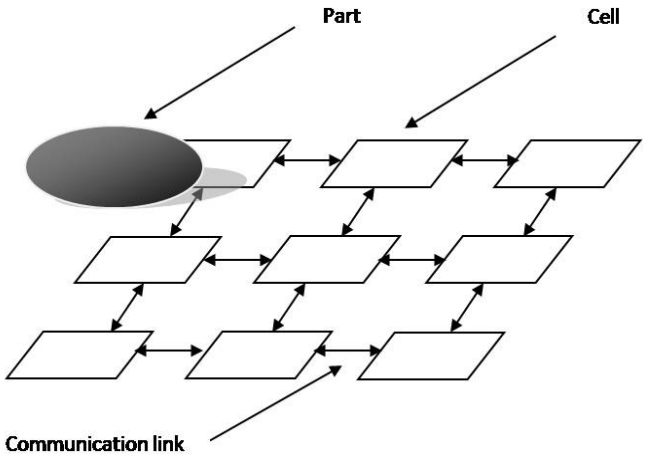

Figure 1. Communication network of the smart surface

Distributed computing (e.g. distributed state acquisition and concurrent pattern recognition) on dedicated architectures like a smart surface is a source of a rich problematic mainly due to the scarcity of resources like number of sensors (each part will recover a small number of sensors), memory size and computing power or the presence of faults. To the best of our knowledge, the literature on sorting and positioning micro parts in a low resolution context is almost nonexistent.

In this paper, we propose techniques for distributed discrete state acquisition, communication management and pattern recognition. In particular, we give a mathematical model of discrete state acquisition and propose several distributed iterative algorithms; i.e. we consider synchronous and asynchronous state acquisition methods. We propose also simple initial points and give convergence results for distributed algorithms. We propose stopping criteria in the synchronous case and in the asynchronous case.

We derive also several techniques for concurrent pattern recognition. These techniques are particularly interesting when cells present faults or when parts are initially positioned any manner on the smart surface. Finally, we introduce SSS, a multi threaded Java smart surface simulator that has permitted us to evaluate and validate experimentally our distributed algorithms on multicore machines.

Section 2 gives more details on the smart surface. Section 3 deals with distributed state acquisition. Pattern recognition techniques are presented in Section 4. In Section 5, we introduce SSS, a multithreaded Java smart surface simulator. Computational results related to pattern recognition are displayed and analyzed in Section 6. Conclusions and future works are presented in Section 7.

II. THE SMART SURFACE

Assembly line workstations need to be fed with well-positioned and well-oriented parts. These parts are often jumbled and they need to be sorted and conveyed to the right workstation. To do so, the following operations must be performed on parts: identification, sorting, orienting, positioning and feeding. Among the most promising solutions to perform these tasks, is the combination of MEMS in order to form a micro robotics array.

There have been numerous projects on MEMS actuator arrays in the past and more particularly in the 1990's. These pioneering research works have developed different types of MEMS arrays that are based on actuators which are either

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pneumatic (see [17] and [19]), magnetic or thermo bimorph, electrostatic or servoed roller wheels (see [16]). Recent research works have been conducted in order to include sensors and to add intelligence to MEMS actuator arrays but these works either failed to propose solutions at a micro-scale or that are fully integrated (e.g. see [2]).

The objective of the Smart Surface project (see [15] and [18]) is to design a distributed and integrated micro manipulator based on an array of micro modules in order to realize an automated positioning and conveying surface. Each micro module will be composed of a micro actuator, a micro sensor and a processing unit. The cooperation of micro modules thanks to an integrated network will allow the system to recognize the parts and to control micro actuators in order to move and position accurately the parts on the smart surface. We consider small parts that cover a small number of micro modules and that are moved via air nozzles actuators (the rectangular holes on the front-side of Fig. 2). Air-flow comes through a micro valve in the back-side of the device and then passes through the nozzle. The advantage of this solution is that the micro actuators, the most fragile part of the surface, are protected. Circle holes (see Fig. 2) are used by the micro sensors to detect the presence of the part on the surface.

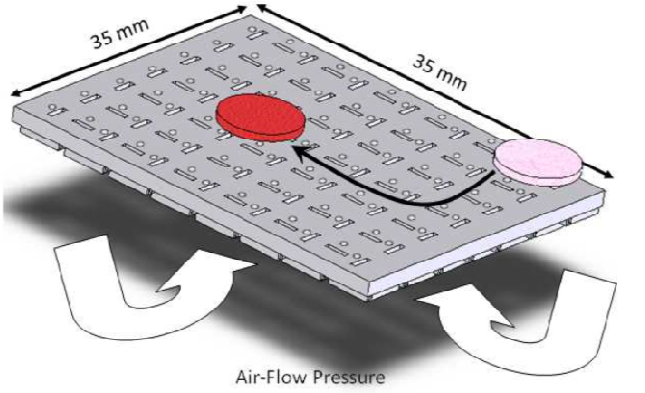

Figure 2. General overview of the Smart Surface

III. Distributed State Acquisition

In this Section, we lay down the mathematical foundations of discrete state acquisition of the smart surface in order to derive and study several distributed synchronous and asynchronous algorithms. For each cell, the problem is to obtain global knowledge of the state of the smart surface, i.e. to know precisely where a part is situated.

A. Mathematical model of distributed state acquisition

Without loss of generality, we assume that there is only one part on the smart surface and one sensor per cell. State acquisition can be modeled as the following fixed point problem: find $x^* \in E = \{0,1\}^{n^2}$ such that x^* is the smallest fixed point which satisfies:

$$x = F(x),$$

where n is the number of cells of the smart surface and F is a mapping from E into E. A vector $x \in E = \{0,1\}^{n^2}$ represents an augmented global state of the smart surface. This vector can be decomposed into sub vectors $x_i \in \{0,1\}^n,\ i \in \{1,\dots,n\}$, where x_i represents an augmented local state of the ith cell. As a consequence, each cell needs only n bits in order to store its augmented local state (similarly, each cell needs at most $4n$ bits in order to store the augmented local state of its neighbors). The augmented local state of a given cell i corresponds to its current vision of the smart surface. The augmented local state can be decomposed into the actual local state of cell i, that is denoted by the scalar $x_{i,i}$ (if there is a part on cell i, then $x_{i,i} = 1$, otherwise we have $x_{i,i} = 0$) and the current knowledge cell i has of the smart surface, i.e. $x_{i,j},\ j \in \{1,\dots,n\},\ j \neq i$. The mapping F permits one to obtain a mathematical formulation of the state acquisition problem and to derive several useful distributed algorithms.

Cells make acquisition of the global state of the smart surface via data exchange, i.e. via messages they receive from their direct neighbors. Let $N(i)$ denote the set of all neighbors of cell i, the mapping F that can be decomposed the same way as vector x, is defined as follows:

$$F_{i,i}(x) = x_{i,i}, i \in \{1,\dots,n\},$$

$$F_{i,j}(x) = x_{i,j} + x_{j,j}, if\ j\ \in N(i), i \in \{1,\dots,n\},$$

$$F_{i,l}(x) = x_{i,l} + \sum_{j \in N(i)} x_{j,l},\ i,l \in \{1,\dots,n\}, l \notin N(i),$$

where the operations $+$ and $\sum_{j \in N(i)}$ are defined as follows: let $a, b \in \{0,1\},\ a + b = 0, if\ a = 0\ and\ b = 0,\ a + b = 1$, otherwise; similarly, $\sum_{j \in N(i)} x_{j,l} = 1\ if\ at\ least\ one\ x_{j,l} = 1$ and $\sum_{j \in N(i)} x_{j,l} = 0$ otherwise.

Definition 1: Distributed synchronous state acquisition can be described via the following successive approximation method (this method is also referred to as a discrete iteration or an iteration on a product of finite sets):

$$x^{k+1} = F(x^k), k = 0,1,\dots$$

Where the initial approximation x^0, is chosen as follows:

$$x^0_{i,j} = 0, if\ j \neq i, i,j \in \{1,\dots,n\},$$

$$x^0_{i,i} = 1, if\ there\ is\ a\ part\ on\ cell\ i, i \in \{1,\dots,n\},$$

$$x^0_{i,i} = 0, if\ there\ is\ no\ part\ on\ cell\ i, i \in \{1,\dots,n\}.$$

Remark 1: Clearly, x^* is not the only fixed point for F. It is possible that the sequence $\{x^k\}$ generated by a discrete iteration starting from $x \in E, x \neq x^0$ remains stationary at a given vector $x', x' \geq x^*$, where the order relation is component wise, i.e. $x'_{i,j} \geq x^*_{i,j}, \forall i,j\ \in \{1,\dots,n\}$. A simple illustration can be obtained by choosing $x \in E$ such that $x_{i,j} = 1, \forall i,j \in \{1,\dots,n\}$. In this case, we clearly have: $x = F(x)$. However, the values of the component $x_{i,i} = 1, \forall i \in \{1,\dots,n\}$ derived from x do not correspond to the actual local state of the cell of the smart surface, unless the part covers completely the surface. This shows the importance of choosing a good initial approximation in order to converge to a fixed point that makes sense in term of state acquisition. We shall see in the sequel that the above defined initial vector x^0, which is in fact a sub

solution, i.e. which satisfies $x^0 \leq x^*$ (the inequality being considered component wise), is a good starting point in order to converge to the solution x^* of the fixed point problem that makes sense in term of state acquisition.

The reader is referred to Robert [6] for a study on mathematical and algorithmic aspects of discrete iterations.

Theorem 1: The mapping F is monotone.

Proof: from the definition of the mapping F, we clearly have $F(x) \leq F(x'), \forall x, x' \in E \; such \; that \; x \leq x'$; Q.E.D.

Theorem 2: The distributed discrete iteration $\{x^k\}$ converges to x^*.

Proof: from the definition of mapping F, we have

$$x^0 \leq x^1 = F(x^0).$$

Moreover, we have

$$x^k \leq x^{k+1} = F(x^k), \forall k = 1,2, \dots$$

$$x^k \leq x^*, \forall k = 1, 2, \dots$$

Since the mapping F is monotone, $x^0 \leq x^*$ and $x^* = F(x^*)$. We denote by d a discrete distance on $\{0, 1\}$. We have:

$$d(x_{i,j}, x'_{i,j}) = |x_{i,j} - x'_{i,j}|, \forall x, x' \in E, \forall i, j \in \{1, \dots, n\}.$$

Let d^m be the Manhattan distance on E, we have:

$$d^m(x, x') = \sum_{i=1}^{n} \sum_{j=1}^{n} |x_{i,j} - x'_{i,j}|, \forall x, x' \in E.$$

We note that $d^m(x, x')$ is finite for any $x, x' \in E$. As a consequence, the distributed discrete algorithm $\{x^k\}$ converges monotonically to x^* in finite number of iterations; Q.E.D.

Let us denote now by d' the largest Manhattan distance of the smart surface.

Theorem 3: The number of iterations of the discrete algorithm is bounded by $d' + 1$.

Proof: The distributed discrete iteration starting from $x^0 \in E$, generates a monotone sequence $\{x^k\}$ of vectors of E. Time after time, each cell makes acquisition of the augmented local state of its neighbors via messages it receives from them and combines these augmented states with its own augmented state in order to produce an updated augmented state, i.e. a more accurate vision of the state of the mart surface. At each new iteration, cells gain a more accurate vision of the actual discrete state of the smart surface by a unit of distance. This corresponds to a link between two cells along each direction. Finally, the sequence converges to the fixed point $x^* \in E$ which is such that $x^*_{i,j} = x^*_{j,j}, \forall i, j \in E$; this shows that at convergence, all augmented local states are similar and that all cells have the same vision of the global state of the smart surface). Q.E.D.

For a rectangular smart surface with size $a \times b$, at most $(a - 1) \times (b - 1)$ sequences of communications are necessary to make acquisition of local states and at most $(a - 1) \times (b - 1) + 1$ iterations are necessary to obtain the solution.

Implementation

For simplicity of notation, we denote in the sequel by N_i the set of neighbors of node i. The jth neighbor of node i is denoted by $n_i(j)$. The behavior of the distributed synchronous discrete algorithm can be represented as follows.

For *i* from 1 to *n* do

  For *k* from 1 to $d' + 1$ do

    $x_i^k := F_i(x^{k-1})$

    For *j* from 1 to $card(N_i)$ do

      send x_i^k to $n_i(j)$

    End do

    For *j* from 1 to $card(N_i)$ do

      receive x_j^k from $n_i(j)$

    End do

  End do

End do

Distributed synchronous discrete algorithm

The distributed algorithm converges in finite time. It is nevertheless possible to derive simple stopping tests in order to reduce the number of iterations.

Improved local stopping test

We present now a distributed stopping test designed in order to stop iterations at global convergence by using only local data.

Definition 2: The local stopping test stops the computation of cell i at iteration k if $\exists j \in \{1, \dots, n\}$ such that $x_{i,j}^k = 1$ and $x_i^k = x_i^{k-1}$.

The above stopping test is only based on local data, i.e. a comparison of the augmented local state x_i at two consecutive iterations k and $k - 1$. Nevertheless, this test permits a cell to stop computation at global convergence since if a component of x_i is equal to one, then the cell "knows" that there is a part on the smart surface and if the augmented local state does not change from an iteration to another, then the shape of this part is stationary. We recall that the "horizon" of a cell increases by one unit of distance along each direction at each iteration.

Let $N_{a,i}^k$ denote the set of active neighbors of cell i at iteration k, i.e. the set of neighbors for which the improved local stopping test presented in Definition 2 is not satisfied at iteration k. Let $n_{a,i}^k(j)$ denotes the jth active neighbor of cell i at iteration k. The behavior of the improved distributed synchronous discrete algorithm can be represented as follows:

For i from 1 to *n* do

  While local stopping test is not satisfied

    $k := k + 1$

    derive $N_{a,i}^k$

    $x_i^k := F_i(x^{k-1})$

For j from 1 to $card\left(N_{a,i}^{k}\right)$ do

send x_i^k to $n_{a,i}^{k}(j)$

End do

For j from 1 to $card\left(N_{a,i}^{k}\right)$ do

receive x_j^k from $n_{a,i}^{k}(j)$

End do

End While

End do

Improved distributed synchronous discrete algorithm

B. Distributed asynchronous algorithms

In the above subsection we have presented a first model of distributed state acquisition in the synchronous case. We present now a mathematical model in the more general asynchronous context where each cell can perform updating phases at its own pace, i.e. computation can be done without order nor synchronization. We derive convergence results by using the general convergence theorem of Bertsekas (see [7]). We propose also a stopping method.

We assume that there is a set of times $T = \{0,1,2,\dots\}$ at which one or more sub vectors $x_i, i \in \{1,\dots,n\}$, of vector x are updated by some cells. We denote by $T(i)$ the subset of times at which the sub vector x_i is updated. Let $L_i = \{s_{1,i}(k),\dots,s_{n,i}(k)\}$ be the subset of labels used during the updating phases of cell i with:

$$0 \le s_{j,i}(k) \le k, \forall\, j, i \in \{1,\dots,\mathrm{n}\}, \forall k \in T(i).$$

We assume that $\lim_{k\to\infty} s_{j,i}(k) = +\infty, \forall j, i \in \{1,\dots,n\}$, this assumption guarantees that new values of the components of the sub vectors are used as computations go on. We also assume that the sets $T(i)$, $i = \{1,\dots,n\}$, are infinite; this assumption guarantees that no component of the iterate vector is abandoned forever. In particular, cells will not stop their computations before convergence.

We denote by L the set of labels used during the computations performed by the different cells.

Definition 3: Distributed asynchronous state acquisition can be described via the following successive approximation method denoted by (F, x^0, T, L), where x^0 is the initial approximation defined in Section II.A.

$$x_i^{k+1} = F_i\left(x_1^{s_{1,i}(k)},\dots,x_n^{s_{n,i}(k)}\right), \forall k \in T(i),$$
$$x_i^{k+1} = x_i^k, \forall k \notin T(i),$$

Theorem 4: The distributed asynchronous discrete iteration (F, x^0, T, L) converges to x^*.

Proof: In order to show convergence of the asynchronous algorithm (F, x^0, T, L) we build a sequence of level sets which satisfies the conditions of the general asynchronous convergence theorem of Bertsekas, see page 431 in [7].

Let $E^0 = \{x \in E \,/\, x^0 \le x \le x^*\}$, we define the sets

$$E^k = \{x \in E \,/\, F^k(x^0) \le x \le x^*\}.$$

The so called synchronous convergence condition of Bertsekas

$F(x) \in E^{k+1}, \forall k, \forall x \in E^k$, and every limit point of $\{x^k\}$ is a fixed point of F if $x^k \in E^k, \forall k$, is satisfied. This result follows from Theorem 2, the monotone property of mapping F and the fact that x^* is the smallest vector such that $x = F(x)$.

The so-called box condition of Bertsekas, i.e.:

$$E^k = E_1^k \times E_2^k \times \dots \times E_n^k, \qquad \forall k = 0,1,2,\dots$$

is also satisfied since the level sets E^k are Cartesian products of subsets $\{0,1\}$. As a consequence, the general asynchronous convergence theorem of Bertsekas applies. Q.E.D.

We note that the sequence of nonempty subsets E^k satisfies:

$$E^\infty \subset \cdots \subset E^{k+1} \subset E^k \subset \cdots \subset E^0,$$

and

$$E^\infty = \{x^*\}.$$

The reader is also referred to Radid [8] for various results related to asynchronous discrete iterations.

Among the many interests of distributed asynchronous iterations, one can quote the better efficiency of the algorithms since each cell goes at its own pace and there is no waiting time for synchronization. This is particularly true in the case of monotone convergence, where the use of last updates permits always one to improve the iterate vector. One can quote also fault tolerance since distributed asynchronous iterations tolerate some messages losses (see [7]).

In the case of a cell fault, a distributed asynchronous algorithm may end with a vector slightly different from x^*, however, there will be no deadlock with such an algorithm.

Implementation

In this subsection, we show how asynchronous algorithms have been implemented. We consider also convergence detection of asynchronous algorithms. Several procedures can be used in order to detect convergence of distributed asynchronous discrete iterations. One can use for example the Dijkstra and Scholten procedure [9] (see also [10] and [11]). The reader is also referred to El Baz [12] for a method based on level sets. The procedure in [9] relies on generation of activity graph and acknowledgement of messages. Initially, only one cell is active, i.e. the so-called root that is denoted by R. The cell R starts computation and sends messages to its neighbors; these messages activate the neighbors that become the so-called sons of R and so on. All cells become eventually active. All messages are acknowledged at once but activation messages of father that are acknowledged only when a son becomes inactive. The activity graph moves on according to the messages received and satisfaction of the conditions: $x_i^{k+1} = x_i^k$. A cell sends messages to its neighbors if and only if it is active and the above condition is not satisfied. Finally, the algorithm stops when the cell R stops; i.e. all local stopping criteria are satisfied and there is no message in transit in the system. This type of convergence detection method is quite natural in the context of discrete iterations since it is not necessary to modify the distributed asynchronous iterative algorithm so that it converges in finite time.

Let us denote by Active(i) the logical variable that stores the behavior of the ith cell: if Active(i) is True, then the ith cell performs computation. If Active(i) is False, then the ith cell does nothing. Initially, all cells are inactive, but R. A cell becomes active when receiving a message. A cell i becomes inactive when the following extended local asynchronous stopping criterion is satisfied.

Definition 4: The extended asynchronous local stopping test is given by: $x_i^k = x_i^{k-1}$ and all cells activated by cell i are inactive.

All cells can be activated many times but the root, R, which is active only once. Finally, the algorithm stops when R becomes inactive. In the sequel, we shall denote by isend and ireceive, respectively, nonblocking send and receive, respectively. These communication primitives permit one to implement asynchronous communication.

For i from 1 to n do

  While Active(R) = True

    If Active(i) = True then

      $k := k + 1$

      $x_i^k := F_i\left(x_1^{s_{1,i}(k)}, \dots, x_n^{s_{n,i}(k)}\right)$

      If $x_i^k \neq x_i^{k-1}$, then

        For j from 1 to $card(N_i)$ do

          isend x_i^k to $n_i(j)$

        End do

      End if

      For j from 1 to $card(N_i)$ do

        ireceive x_i^k to $n_i(j)$

      End do

  End While

End do

Distributed asynchronous discrete algorithm

Formal proofs of validity for this type of algorithm including convergence detection method have been established in [7] and [11].

IV. Concurrent Pattern Recognition

Once distributed state acquisition has been performed, the concurrent pattern recognition phase can begin. We propose a simple concurrent pattern recognition method whereby cells do not communicate. Basically, cells compute concurrently several contour based differentiation criteria like number of components of vector x_i with value 1 such that there exists $x_j = 0, j \in N(i)$ or region-based criteria like number of components of vector x_i with value 1, i.e. surface like criteria, or maximum length between 1 of the part. The criteria considered in this paper are detailed in [13]. Finally, we note that to the best of our knowledge, there are relatively few papers in the literature on pattern recognition methods in the low resolution context. We mainly refer to Ishida [14], for different approaches related to low resolution character recognition and to Tabbone [22], for a novel approach based on the Radon transform for complex shapes identification.

The value of the different criteria can vary according to the orientation and position of the part on the smart surface. In the case of part rotation, for example, we have noted that the surface of 3x3 square, where the unit of distance is the length of a cell, can vary from 9 to 13, according to the orientation of the part on the smart surface, see Fig. 3 obtained with SSS, a multithreaded smart surface simulator that will be detailed in the next section.

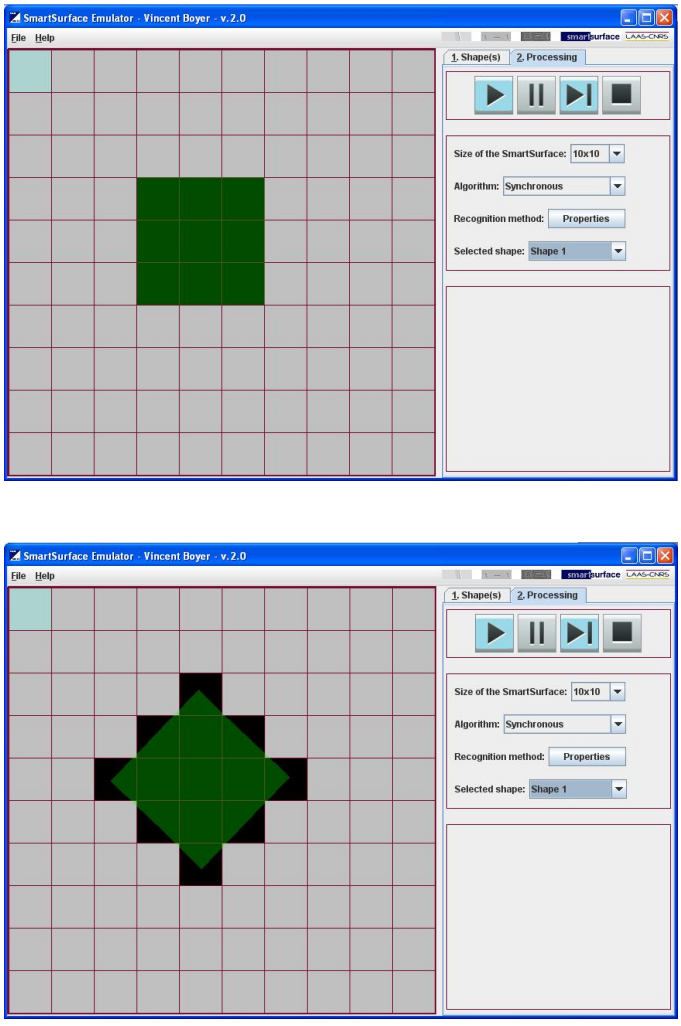

Figure 3. Example of different surface values for the same square with different orientations (SSS screenshots)

In the sequel, we present two new approaches for part differentiation.

The first approach relies on the use of a single reference position for each part. Each cell compares computed values of the criteria for the current position of the part on the smart surface with values of criteria of each part obtained for a

single reference position (those values are stored in a database of registered parts). We propose to compute gaps between the measured criteria and the criteria value of registered parts for differentiation purpose. This method is particularly interesting when some cells present faults.

Another particularity of the first approach is to consider only a subset of well known criteria like surface or perimeter of the part. The criteria that amplify tiny differences between parts, like product of the differences between consecutive columns and consecutive line are discarded. In the sequel, the number of criteria considered will be denoted by q. Let m denote the number of different parts. Let $r_i(j)$ denote the reference value of ith criterion of the jth part (those values are computed offline). Let c_i denote the value of the ith criterion of the part on the smart surface. Each cell computes the following gaps:

$$g(j) = \frac{1}{q}\sum_{i=1}^{q}\left|\frac{r_i(j)}{c_i} - 1\right|, j \in \{1, \dots, m\}.$$

The second approach relies on the use of a set of reference positions for the different parts on the smart surface. We take into account rotations of parts with one degree increments. Without loss of generality and for symmetry reason, only rotations from 1 up to 45 degrees can be considered. Let $D = \{1, \dots, 45\}$. We denote by $r_i^d(j)$ the reference value of ith criterion of the jth registered part rotated by d degrees; those values are also computed offline. We denote by $C(j)$ the set of all reference values for part j, $C(j) = \left\{\left(r_1^d(j), \dots, r_q^d(j)\right), d \in D\right\}$. Each cell computes the following gaps.

$$g'(j) = min_{d\in D}\left\{\frac{1}{q}\sum_{i=1}^{q}\left|\frac{r_i^d(j)}{c_i} - 1\right|\right\}, j \in \{1, \dots, m\}.$$

We note that the former gap, g, presents the advantage to require a limited amount of memory and a small computing time, while the latter gap, g', permits one to expect better differentiation of parts, particularly in the case where parts can have any orientation on the smart surface.

Decision making concerning pattern recognition at each cell relies on the respective values of the gaps. The pattern j that is chosen corresponds to the gap $g(j)$ or $g'(j)$ that is the closest to zero. We note that all cells make the same computation concurrently and thus take the same decision.

Concurrent decision making based on gaps is particularly interesting with respect to fault that may occur on the smart surface, i.e. sensor failures or parts positioned any manner on the smart surface. The use of gaps is also interesting with respect to recognition of pattern slightly modified, i.e. parts that present tiny faults.

V. SSS, A MULTITHREADED SMART SURFACE SIMULATOR

We present now SSS, a smart surface simulator developed at LAAS-CNRS. The simulator SSS has permitted us to evaluate distributed synchronous and asynchronous state acquisition algorithms and concurrent pattern recognition methods. SSS is a multithreaded Java code that runs on multicore machines.

SSS has permitted us to validate experimentally the distributed algorithms and to study in detail communications between cells, stopping criteria and the efficiency of the proposed methods. The reader is referred to the site [5] for some demos with SSS.

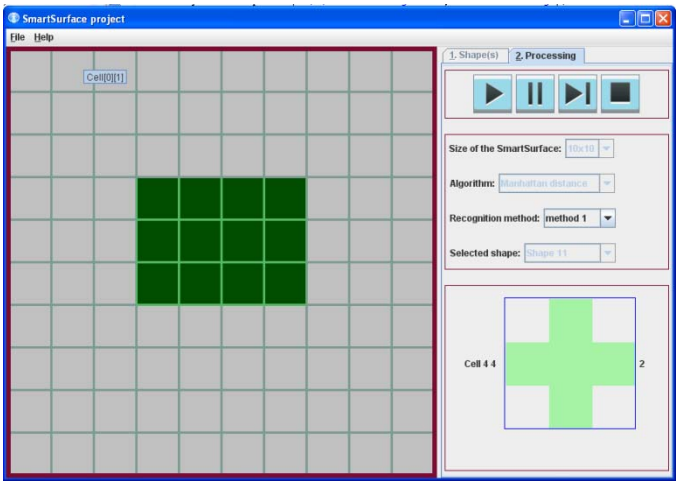

Figure 4. SSS smart surface window (left) and "extended" local state window of a given cell at iteration 2 (right)

SSS permits one to build a smart surface that has any size and different patterns like squares, rectangles, L shapes, I shapes and so on, that will become references or that will correspond to a given part. SSS permits one also to place the generated patterns everywhere on the smart surface. It is possible to rotate shapes on the smart surface and to introduce sensors faults (see Fig. 3, for a square shape). SSS allows one to choose a synchronous or asynchronous distributed state acquisition algorithm, to carry it out and to display dynamically the augmented local state of any cell (see right window of Fig. 4 that corresponds to iteration 2). One can also have a dynamic view of the activity graph of the smart surface. One can choose criteria and a differentiation method, e.g. gaps based methods or differentiation methods studied in [13]. Finally, one can display the results of the pattern recognition phase for the different criteria selected. SSS permits one also to display some statistics.

VI. TESTS

The multithreaded Java smart surface simulator SSS has been carried out in parallel on a multicore machine with Intel Quadro Xeon 3.0 GHz processor.

In this section, we compare a first series of results obtained with SSS for the gap methods proposed in Section IV and the total differentiation method presented in [13]. We have considered three parts: a square, the so-called Sq part, an L shaped part and a I shaped part. All parts have been placed randomly 200 times, leading to 200 draws with SSS. We classified the criteria according to their performance. For each draw, we have computed the values of 17 criteria and we have

applied the total differentiation method which gives the differentiation rate. The criteria were afterwards classified according to the differentiation rate and only the criteria with the best differentiation rates were selected. Table I displays results for the best two criteria: S and A, respectively, were S denotes the surface and A the product of angles of type "V", respectively (see [13]). For 200 draws, we note that the criterion S has correctly differentiated the part Sq in 37% of cases.

TABLE I. DIFFERENTIATION RATES FOR THE CRITERIA A AND S

Criteria	Sq	I	L	Average
S	37.00%	52.00%	57.30%	48.76%
A	33.50%	40.50%	48.50%	40.83%

In the second test, we are interested in part differentiation via a combination of the criteria S and A. Table II shows the differentiation rate obtained by using the criteria combination. We note that the part Sq was correctly differentiated in 59% of the cases; which is better than with S or A alone. The average differentiation rate was increased from 48,76% (for S alone) and 40.83% (for A alone) up to 67.16% for the combination of A and S.

TABLE II. DIFFERENTIATION RATES FOR CRITERIA COMBINATION

Criteria	Sq	I	L	Average
A and S	59,50%	74,00%	68,00%	67,16%

We compare now the results of the above differentiation method with those obtained with the methods based on gaps introduced in Section IV of this paper. Table III displays the results obtained with the gaps g.

TABLE III. DIFFERENTIATION RATES WITH THE FIRST GAP

Criteria	Sq	I	L	Average
S	100%	99.00%	98.00%	99.00%
A	100%	99.00%	78.00%	92.33%
A and S	100%	100%	96.50%	98.83%

Table IV gives the results obtained with the gaps g'.

TABLE IV. DIFFERENTIATION WITH RATES WITH THE SECOND GAP

Criteria	Sq	I	L	Average
S	100%	99.00%	98.00%	99.00%
A	100%	99.00%	78.00%	92.33%
A and S	100%	99.50%	79.00%	92.83%

These results show that the methods based on gaps g and g' improve the differentiation rate in the following cases:
- with a single criterion, e.g. the criterion S, the differentiation rate is improved from 48.76% (see first row of Table I) to 99% for g (see first row of Table 3) and 99% for g' (see first row of Table IV).
- with several criteria, the combination of criteria also improves the differentiation rate from 67.16% (see first row of Table 2), to 98.83% (see third row of Table III) and 92,83% (see third row of Table IV), respectively, for g and g', respectively.

We conclude that the differentiation methods based on gaps give better results than the total differentiation method presented in [13] when parts can have any orientation on the smart surface. Additionally, one criterion alone may be sufficient to reach almost 100% differentiation rate.

VII. CONCLUSIONS AND PERSPECTIVES

In this paper, we have considered a smart surface for conveying, positioning and sorting micro parts. We have laid down the mathematical foundations of smart surface state acquisition. We have proposed stopping criteria and several distributed synchronous and asynchronous algorithms and we have established convergence results for the studied methods. We have also proposed a concurrent pattern recognition method based on gaps. Finally, we have presented SSS, a multithreaded Java smart surface simulator that we have developed in order to evaluate and validate distributed algorithms and we have displayed and analyzed a first series of results for randomly generated instances with SSS.

Future directions of research concern fault detection and solutions that propose degraded but everlasting behavior particularly in the synchronous case.

We shall consider concurrent pattern recognition methods that exploit smart surface natural parallelism, e.g. each cell i can apply a mapping T_i to x_i and compute criteria. Typical mappings T_i can be some rotations. This kind of preconditioning can enrich pattern recognition.

We shall also study combined pattern recognition and part motion; it may be efficient to recognize a part while moving it on the smart surface.

It may also be interesting to derive pattern recognition techniques that are not criteria based and which exploit directly the part code.

Finally, actual implementation on the distributed smart surface must be made in order to complete the study.

We believe MEMS-based smart surfaces to have great industrial impact for manipulating micro parts in many areas like semiconductor industry and micromechanics.

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