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Robot Handling of Flat Textile Materials

The authors present a robotic system incorporating vision and force/torque sensing for handling flat textile materials and describe the results of experiments to measure the accuracy and reliability of the system for a variety of representative handling tasks for textile materials.

Keywords: Robotics, handling of flexible materials

Automatic Handling Systems that can be reprogrammed to perform a different task in relation to *rigid* objects are readily available. These are often robot systems and the reprogramming involves defining a new set of end-effector trajectories that can be repeated. Some systems have also been developed that are capable of adapting to changes in the working environment and to well defined variations in rigid work-pieces.

Robot handling of *non-rigid* materials (NRMs) has received attention in the past but most of the systems deal with specific tasks [1,2]. NRMs handling presents additional problems as their shape, position, orientation and other physical and mechanical properties can vary in unpredictable ways, depending on the dynamics of the material, on the environmental conditions and also on the output of previous handling.

As a result, handling operations cannot be deterministically programmed and a system equipped with sensors that is capable of identifying and reacting appropriately to deformation and displacement produced by weight, dynamic and gripping forces is needed. A theoretical fundamental understanding of such systems has not yet been achieved. At this point it is unrealistic to propose a system capable of handling all non-rigid materials as there would be a number of diverse requirements.

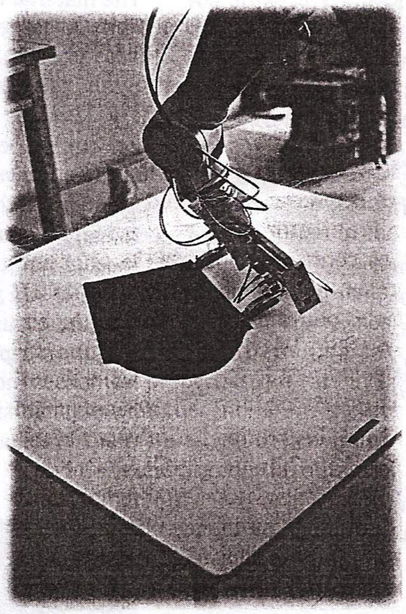

Figure 1. Grasping.

The primary purpose of the work presented here is to generate knowledge through experimentation regarding the design of an automatic system capable of handling flat textile materials. Specifically: a) to identify the type of sensors and processing of sensory information required for the system to be capable of adapting to changes during handling; b) to identify the control needs of the required handling tasks; and c) to encompass general features which can be identified across a broad range of NRM types and their handling requirements. Thus, an investigation of the handling problems related to a range of NRM across industrial sectors has been initially performed in order to identify, analyze and categorize their handling requirements. As a result, a tree structure of handling operations and sub-operations was built. Sensing and control requirements for each handling operation and sub-operation were specified as well as techniques to deal with sensory data processing and control problems involved in the execution of every task. Algorithms according to the specifications were developed and implemented in software and finally a lab unit was constructed in order to experiment with the execution of the selected tasks on a sample set of materials. The knowledge and experience gained out of this procedure will be applicable to all cases where similar handling requirements occur. The laboratory setup used and the

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handling techniques for manipulating flat materials have been described in detail in [10]. In this paper we focus on implementation issues and experimental results.

The paper is organized as follows: First, the handling tasks chosen, as well as the sensing and control problems, are described. Then implementation issues and the laboratory system developed for experimentation is described. The following section presents the results of experimentation and, finally, some concluding remarks are made.

THE HANDLING PROBLEM

A number of handling tasks representative of a wider range of handling procedures have been chosen. These are: 1) Grasping; 2) Laying; 3) Folding; and 4) Flattening of flat materials. A handling strategy has been planned for each. A brief description of these tasks follows. Also the sensing and control problems arising from the chosen handling strategy are described.

Grasping

This task involves grasping the material (which lies flat on a table) along one of its edges and consists of the following two phases: a) identifying and locating in real space the edge to be grasped; and b) moving the arm in order to grasp the material. During the first phase, an image of the material is acquired by a fixed calibrated camera. The perimeter of the material and the edge to be grasped are identified in the image and their image co-ordinates are calculated. Real X,Y,Z, world co-ordinates are calculated out of the image co-ordinates, the Z co-ordinate being known (it coincides with the level of the table). Finally, the required arm position and orientation are calculated. During the second phase, the arm is moved just before the edge to be grasped with the gripper parallel to it and at a distance of about 1 cm over the table's surface. A two attachment point gripper with flexible attachment plates is assumed. Closed loop control of the force applied on the table by the gripper's plates as the arm starts moving vertically downwards, ensures contact of the plates with the surface of the table. Finally the arm is moved horizontally and towards the edge of the material, the lower gripper's plates slide underneath the material, and the gripper is closed (Fig. 1).

Laying

The purpose of this task is to lay the material at a desired location and orientation on the table's surface. Two strategies have been planned for laying.

Laying by Using the Edge of the Table

According to this strategy, the material is being dragged over one of the table's edges (Fig. 2). Initially, it hangs loose, being grasped by the gripper. It is positioned in such a way that its upper edge is located just before and higher by about 5 cm from the edge of the table to be used and it is already oriented as desired. The arm will move along a direction so that this orientation will be maintained. A camera is positioned above the table with its visual axis at an angle of 30° with the vertical and in a way that the edge of the table, over which the material is being dragged, appears at the lower area of the image. The arm moves horizontally at a distance of 5 cm above the surface of the table, dragging the material over the edge of the table. Images of the moving material are continuously grabbed and a signal is transmitted to VAL-II by the vision system, when the rear edge of the material is monitored to be on the table. The arm stops and the gripper opens to free the material.

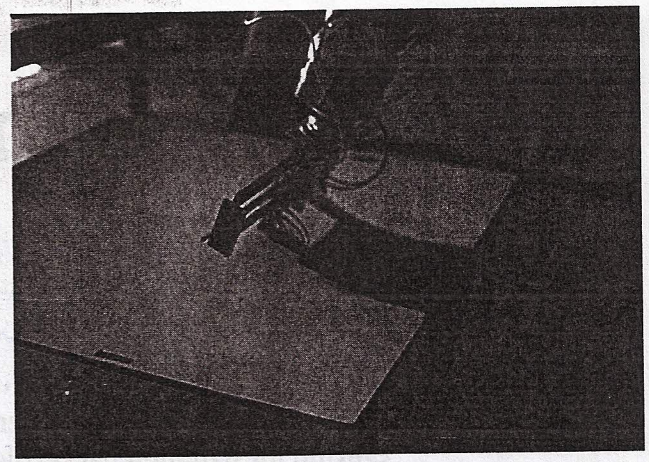

Figure 2. Folding.

Laying by Dragging

The material hangs loose, being grasped by the gripper so that its free rear edge is positioned just over the table. The arm moves vertically downwards until contact of the free rear edge of the material with the surface of the table is accomplished. The dragging action starts with the arm moving by small linear motion segments of constant length, each consisting of a vertical (downwards) and a horizontal component. The idea underlying this strategy is that if the free rear edge keeps moving because it is being dragged by the rest of the material, then tangential stresses applied all over the length of the material will prevent it from getting folded (Fig. 3). Therefore images of this edge are being continuously acquired (in real time), its displacement is calculated, and the next vertical and horizontal motion segments are calculated accordingly. Since image acquisition and processing needs to be carried out on line, a fast technique for image processing is required in this case.

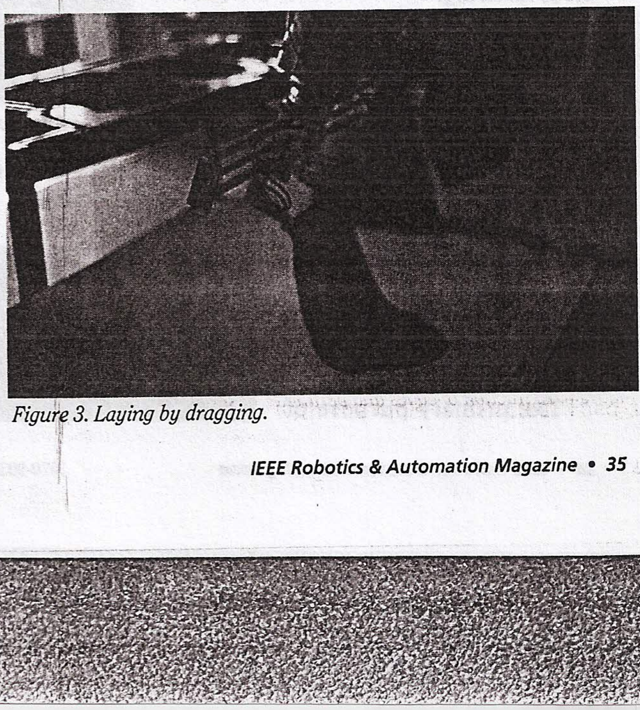

Figure 3. Laying by dragging.

Folding

Folding consists of grasping one edge of the material, and putting it over an opposite one, so that finally the two edges coincide one over the other (Fig. 4). A camera is positioned above the table with its visual axis forming an angle of 30° with the vertical, in a way that the target edge appears at the lower edge of the acquired image. The edges of the perimeter of the material are extracted, the folding edge is identified and its X,Y,Z co-ordinates in the robot's base co-ordinate system are calculated. The target edge is also identified in the image and the relative distance between the two edges is calculated. The arm performs a complete grasp as described above. Then it starts moving along a trajectory which is being calculated in real time by a closed loop control scheme using visual information feedback. This trajectory is the surface of a cone whose angle is initially calculated from the angle formed between the two edges to be matched. In practice the target edge moves during the folding operation; therefore it has to be continuously monitored. The radius of the cone mentioned above is modified to compensate for the target edge displacement.

Figure 4. Laying using the table's edge.

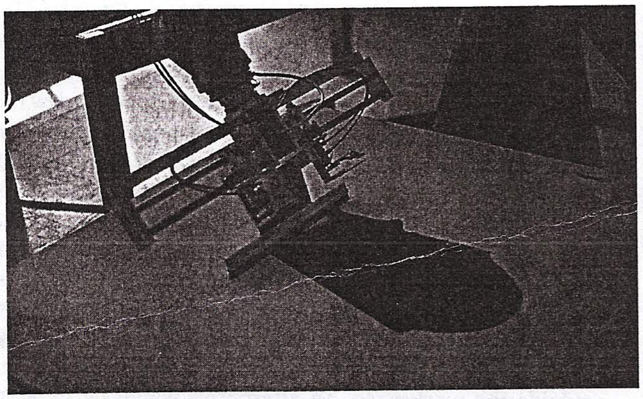

Figure 5. Flattening-sweeping.

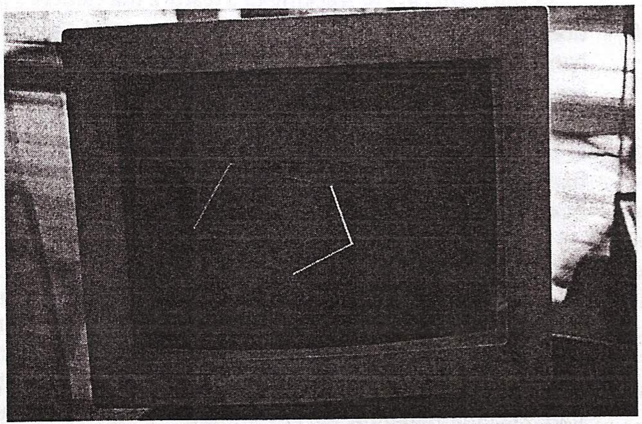

Figure 6. Extraction of edges and perimeter of shape.

Flattening-Sweeping

Flattening aims to eliminate deformation on the material's surface (in the form of wrinkles and folds), by smoothly sliding a brush tool (attached to the robots end-effector) over its surface (Fig. 5). First the direction along which the major problem lies is calculated by processing two images of the material acquired under special lighting conditions. Then the sweeping action takes place in a direction perpendicular to the deformation. During sweeping, closed loop control of the force applied between the brush tool and the table's surface ensures contact of the tool with the material. One edge of the material is fixed by means of auxiliary devices.

Elementary Operations

In order to carry out the handling tasks described above, several simple operations that involve either processing of sensory data or control had to be implemented. These are listed in Table 1 along with a brief description.

IMPLEMENTATION ISSUES—LABORATORY SETUP

The lab setup used for implementation and experimentation is presented in Fig. 7. Mainly it consists of the robot manipulator, the vision sensing system and the force/torque sensing system.

The vision system consists of the Frame Grabber, the PC, the two cameras and the lighting equipment.

The force sensing module consists of the Force/Torque sensor and its controller. The vision system communicates with the robot controller through either a serial RS232 interface or through signals transmitted over the PC's parallel port while the force/torque sensing system is using its own parallel interface.

More specifically, the following equipment was used: a) a robot manipulator PUMA 761 with a VAL-II Controller from UNIMATION; b) a 80486 PC with auxiliary boards; c) a Frame Grabber FG-100; d) a monochrome camera and a color camera; e) a Force-Torque sensor from ATI (model F/T 30/100), mounted on the manipulator's wrist; f) a gripper with two attachment points movable by a servo-motor along a linear axis, specially designed in our lab and constructed for handling flat materials purposes. It is also mounted on the manipulator's wrist next to the Force/Torque sensor; g) complementary equipment, such as tools that were constructed for the robot end-effector, lighting equipment and supports for camera positioning in the robot workspace.

The laboratory system was constructed and all the required algorithms for sensory data processing [3,4] and control [5,6,7,8,9] have been specified and developed. A separate software and hardware module has been developed for every handling task and tested out by experimentation. Integration into a single system incorporating the facilities of all modules has been performed building a handling system equipped with vision and force/torque sensing capabilities.

Table 1: Primitive operations.

Operation	Description
Identification of wrinkles and folds	Identify and describe deformation on the material's surface (orientation and size of wrinkles & folds) by processing an acquired image
Extraction of edges and perimeter of shape	Identify and describe the perimeter of shape and the edges of the material (Figure 6)
Tracking of a moving edge	Track one of the material's edge while moving
Calculation of area	Calculate the area of the material's surface
Calculation of X,Y,Z co-ordinates from image representation	Calculate the absolute X,Y,Z co-ordinates of the material in the arm's workspace by the inverse transform of its co-ordinates in the image
Trajectory generation for laying by dragging	Generate on-line the trajectory the arm should move along, using visual feedback information concerning the position of the free rear edge
Trajectory generation for folding	Calculate on-line the motion segments of the arm by using visual feedback information concerning the displacement of the target edge of the material
Trajectory generation for sweeping	Calculate the arm trajectory using force-torque sensing information, describing the appliance force between the gripper's endpoints and the table's surface

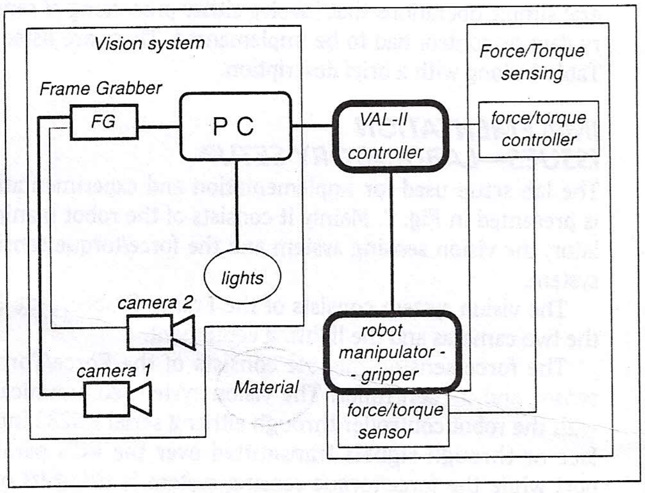

Figure 7. Laboratory set-up.

We will now address some implementation issues that affect the performance of the handling system.

Type and Collection of Sensory Information

The system developed mainly depends on vision sensing information. Therefore problems arising in the collection and processing of such information strongly affect the performance of the whole system.

Vision

Vision is used for: a) location of objects in the arm's working space (in the case of a handling strategy that requires calculation of absolute object position); b) inspection of these objects (material) in detail to identify and describe specific features (e.g., deformation); and c) tracking of a specific feature of the material (e.g., the displacement of an edge while the material is moving) in order to use this feature as feedback in closed loop control schemes. As experimentation has shown, different limitations and requirements apply in each one of the above cases.

In the first case of object location, a view including the arm, the material and in general all the working space is required. Therefore the camera should be positioned at some distance (2m or more) away from these objects. This results in low resolution in the acquired image which in turn results in some error in the identification of object boundaries in the image and in the calculation of their absolute co-ordinates in X,Y,Z, space. For example, if an area of 4 square meters is viewed in a 512x512 pixels image by the camera, then the best of accuracy that can be reached with this configuration is 3.5 mm. However, these errors are not critical for the operations in this case.

In the second case of object inspection, a closer view of the specific object under consideration is required because errors of 3.5 mm are critical (e.g., in the calculation of angles between successive edges, or identification of edges intersection points). Therefore a camera positioned close to the material (30-50 cm) is required. However, this camera positioning would cause problems in manipulation since the camera would be an obstacle in the arm's workspace. In our experiments this second camera was able to move vertically to approach the material and then retire at a resting position outside the workspace. An alternative would be to adopt a moving camera strategy.

In the third case of tracking of a feature the camera's position is operation dependent; from another point of view the handling strategy for the specific operation should take into account the camera positioning. In our case of well defined tasks these problems were easily solved. However, in a general purpose handling system, a moving camera strategy (perhaps mounted on the arm itself) would result in a more flexible system.

Force/Torque

The main use of force sensing in our experiments was the detection of contact of the end effector with the table's surface and the regulation of the force applied. Detection of contact with the table's surface is needed in the grasping and flattening-sweeping handling tasks. During grasping, the contact of the gripper's end plates with the table is detected. Then a

Table 2: Experimentation results.

Task	Mat. Type	Mat. Geom.	Mean abs. Error (mm)	Mean abs. deviation (mm)
Grasping	Blue Linen	Sleeve	E_{L1} : 3.67 E_{L2} : 5.32 E_{L3} : 6.23	D_{L1} : 3.69 D_{L2} : 4.42 D_{L3} : 3.97
Folding	Blue Linen	Sleeve	E_{L1} : 2.76 E_{L2} : 4.58 E_{L3} : 2.80	D_{L1} : 1.21 D_{L2} : 2.44 D_{L3} : 4.01
Folding	Blue Linen	Trouser	E_{L1} : 5.58 E_{L2} : 9.13 E_{L3} : 5.13	D_{L1} : 3.89 D_{L2} : 4.41 D_{L3} : 1.64
Folding	Blue Linen	Front	E_{L1} : 4.06 E_{L2} : 4.54 E_{L3} : 1.30	D_{L1} : 1.22 D_{L2} : 1.50 D_{L3} : 1.14
Folding	Black Jean	Sleeve	E_{L1} : 3.52 E_{L2} : 6.10 E_{L3} : 1.95	D_{L1} : 1.19 D_{L2} : 1.69 D_{L3} : 1.13
Folding	Black Jean	Trouser	E_{L1} : 5.21 E_{L2} : 5.60 E_{L3} : 2.72	D_{L1} : 1.73 D_{L2} : 1.48 D_{L3} : 1.35
Folding	Black Jean	Front	E_{L1} : 4.23 E_{L2} : 5.50 E_{L3} : 2.61	D_{L1} : 1.58 D_{L2} : 1.82 D_{L3} : 1.49
Folding	Black anisotropic	Sleeve	E_{L1} : 10.08 E_{L2} : 4.32 E_{L3} : 1.72	D_{L1} : 3.72 D_{L2} : 2.55 D_{L3} : 0.57
Folding	Black anisotropic	Trouser	E_{L1} : 10.67 E_{L2} : 5.17 E_{L3} : 1.30	D_{L1} : 2.28 D_{L2} : 2.29 D_{L3} : 0.62
Folding	Black anisotropic	Front	E_{L1} : 6.06 E_{L2} : 6.41 E_{L3} : 1.43	D_{L1} : 1.55 D_{L2} : 4.59 D_{L3} : 0.83
Laying	All materials	All geometries	E_{L1}, E_{L2}, E_{L3} equal to arm's accuracy	D_{L1}, D_{L2}, D_{L3} equal to arm's accuracy
Sweep	All materials	All geometries	E_{DS} : 0	D_{DS} : 0

closed loop control adjusts the force distribution between the two contacts points based on the sensor's readings to ensure the parallelism of the tool with the table and the application of an equal force by the two contact points. The end effector is then moved horizontally until the lower gripper plates slide underneath the material and gripping is performed. During flattening-sweeping the contact of the sweeping tool with the material laid on the table is detected and the force applied during the sweeping motion is restricted to values which would not destroy the material.

Because the combined weight of the gripper (5 Kg) and the currently available wrist/torque sensor is far in excess of the weight of the material being handled, the sensitivity and accuracy of the sensor is insufficient to detect the presence of a clothing material at the gripper or measuring the tangential stresses applied to the material when being dragged over the table. The significant gripper-material weight coupled with the arm's vibration causes a permanent varying force to be detected by the sensor which is comparable or even greater in these cases to the size of the expected measure and interferes with it. As a result the range of applicability of force sensing was limited to those cases where the size of measure was by far greater than the size of noise (e.g., detection of contact with the table). A lighter gripping tool, or a different sensor mounting scheme e.g., at the gripper's endplates, could possibly overcome this problem.

In order to identify the presence of the material between the gripper plates and thus to ensure that the material has been successfully grasped, we use specially constructed fuse sensors (e.g., short circuit detection between the gripper's plates); commercially available sensors could be used instead.

Processing of Sensory Data

Vision

A serious problem is the noise present in the acquired image. A slight change in the light conditions causes a great change to the acquired image. In object location this causes a displacement of the material boundaries in pixel co-ordinates. In identification of deformation (wrinkles and folds), which are detected through the shadows and light reflection variations caused by the material's surface, noise causes fictitious shadows. The algorithms should either involve automatic compensation techniques for these problems (which, however, would make them complex and therefore slow) or should alternatively accept input parameters describing light conditions, often in the form of a threshold value (e.g., a threshold value is used to decide that a light intensity variation is due to deformation and not caused by some other reason). Rather than compensating automatically we chose to use a threshold value, which was determined experimentally for various environmental conditions. Color information was not used in our implementation; a monochrome camera could have been used instead. However, the use of color information can be useful in more complicated situations from those examined.

In many cases processing of vision information is required on-line (in real time) and as a result the algorithms developed must be fast and should not involve complex and time consuming techniques. A slow algorithm results in control loop delays that might even drive the system unstable (such reactions have been observed in our experiments). However, some image processing problems require complex algorithms. Simpler and faster algorithms could operate in these cases if some assumptions are made about the material's position and orientation and if some knowledge about the lightning conditions is available. Therefore a compromise should be made between developing general purpose self-dependent but usually slow algorithms, and simpler and faster algorithms which assume knowledge of the handling conditions. In our case, a description of geometrical properties, a brief description of the coloring variation, and parameters describing the weight and stiffness of the material were considered to be known.

Force

The force sensor can directly measure the force and torque along all three directions of the co-ordinate system. Normally no further calculations or processing of force sensory data is required. However, in our case we used filtering of the acquired measures by calculating mean values in order to deal with the noise problem.

Type and Implementation of Control

Another issue of importance is the level at which control of the manipulator is required. In our case a general purpose manipulator, programmable and controllable through a high level programming language (VAL-II) was used. Therefore the control algorithms developed were designed and implemented under the limitations of the specific programming language, and system state accessibility. The main control action is therefore restricted to modifications and adjustments of predefined end effector trajectories based on sensor measures so that final state errors are minimized. Sensor measures involve quantities which influence the final state error. For example, monitoring the target edge position during folding and adjusting accordingly the radius of the cone trajectory followed by the end effector is expected to minimize the final error in folding. Alternative control schemes involving direct controlling of the motor currents or calculating the trajectory by our own algorithms on an external computer and then feeding it back to the manipulator were not implemented. The control level we used reduced system flexibility and speed of task execution. Also the VAL-II communication interface with external equipment (the PC and the force-torque sensing system) is relatively slow.

Communications

A major issue that should be taken into account during the design phase of the system and the algorithms for sensory data processing and control is the requirements for communications between the system sub-modules and also the way these communications are implemented (that is, the software protocol used and the hardware connection). We used RS232 serial interface to transmit instructions to the arm in VAL-II programming language. This proved to be very slow. In fact, more than 50% of the time durations presented in Table 3 are spent on communications. In the case of arm's motion modification in real time a parallel interface was used and simple signals were transmitted instead of complete VAL-II commands, to reach an acceptable speed.

EXPERIMENTATION—RESULTS

Using this laboratory implementation, extensive experimentation has been carried out.

Material types and shapes representative of those actually met in the textile industry have been selected to form a sample set of materials. This consists of 16 sample material pieces, which are combinations of four material types with four material geometries. The material types are: a) a blue linen material; b) a black linen anisotropic material; c) a black Jean material; and d) a multicolored paper material. The material geometries are: a) a sleeve piece; b) a T-shirt back piece; c) a T-shirt front piece; and d) a trousers half piece. Every material shape was approximated by a number of straight lines as shown in Fig. 8.

Measures of final state errors have been defined for each of the handling tasks described previously, in order to measure the accuracy of the system. In grasping, final state errors involve the distance between the final position of the two gripper's plates relatively to the edge of the material being grasped. In folding, the final state errors express the relative position of the edges which should ideally coincide when the material is folded. In laying, final state errors express the relative position of a specific edge, which is usually the grasped

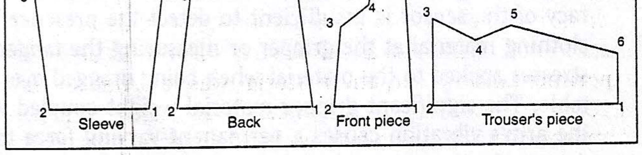

Figure 8. Material geometries in the sampling set.

Table 3: Time requirements.

Handling Task	Average Time
Grasping	5 sec
Laying by dragging	12 sec
Laying by using the table's edge	8 sec
Folding	15 sec
Identification of the state of the material	15 sec
Flattening-Sweeping	8 sec

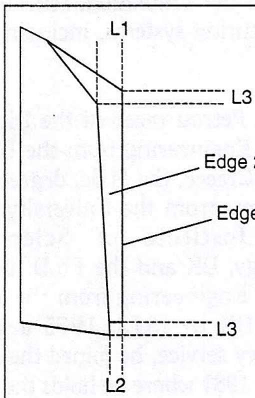

Figure 9. Error measures for folding.

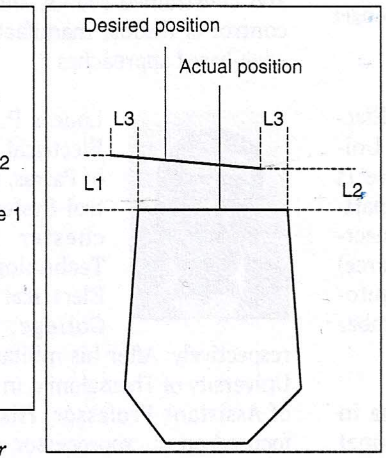

Figure 10. Error measures for laying.

edge, from the desired position. Last in flattening, the final state error expresses the resulting deformation by calculating the difference between the calculated area of the laid material from the area of the material when it is flat.

Each handling task has been executed repeatedly on every sample material. Grasping has been performed 46 times on the first material type and geometry and for different approaching angles of the arm. Folding has been performed 46 times for each combination of material type and geometry except for the paper material (which could not be folded), giving a total of 46x4x3 experiments. In sweeping, 16 experiments have been executed.

Error measurements have been collected and processed. Mean values, and deviations for various combinations of task and materials are presented in Table 2. The notation used is explained schematically in Figs. 9 and 10. In sweeping, E_{DS}, D_{DS} express the mean and deviation of the area difference between the laid material and the material when flat. The values presented in Table 2 have been calculated from the measurements as follows:

a) $E_y=1/N\ (\sum e_i) \quad i=1,\ldots,N \quad e_i=\text{Abs}(y_i - y_d)$

b) $D_y=1/N\ (\sum d_i) \quad i=1,\ldots,N \quad d_i=\text{Abs}(y_i - y_m) \quad y_m=1/N\ (\sum y_i)$

$i=1,\ldots,N,$

where y is the measured quantity, y_d is the desired value and N is the number of measurements.

In laying, the accuracy of the positioning of the material is equal to that of the arm as indicated in Table 2. In all laying experiments, however, the material was laid flat so that sweeping was not subsequently needed. To evaluate the performance of the sweeping task, we had to intentionally lay the pieces of the material in a deformed state.

Time requirements for the execution of the handling tasks is shown in Table 3.

Reliability measures refer to handling task failures. In the case of paper-like material, the absence of friction with the table's surface made it impossible to handle paper with the single arm solution that was initially chosen. In the case of laying by dragging, a possible cause of failure could be an insufficient length of the table as compared to the length of the material to be laid. In our case the length of the table was sufficient for the lengths of the sample materials used. Task failures are also expected with sticky material. Task failures were rare with the range of the material used and thus reliability measures are not given.

CONCLUSIONS

The general purpose of this work is to investigate the parameters involved in the development of a general purpose robot handling system for the handling of flat textile materials. Such parameters are the design rules the manipulating system should obey, the type of sensors and processing of sensory information required for the system to be able to adapt to unpredictable behavior of the material and to environmental changes and the control requirements of the tasks that have to be carried out. The evaluation of such a system on the other hand, should address a range of applications in several categories of materials and handling problems, the degree of its robustness, its applicability in real world conditions with reference to the time required for the tasks to be executed and the accuracy of the manipulation.

A general conclusion is that vision and force/torque sensing combined with fuse sensors provide enough information to overcome the problems arising from the flexibility of the material under consideration. In general, one could say that vision and force/torque sensors of moderate complexity are adequate for the handling tasks considered. The operations presented in the second section (which involve both sensing and control algorithms) can be carried out by software that is not very complex. The execution time for these operations on a 486 PC (Table 3) demonstrate the applicability of the robot handling tasks in practical cases. Finally, unless the parameters involved do not take extreme values (e.g., the material becomes very sticky or excessively heavy) the system presented works well. Of course there is a lot of room for improvement, especially in the design of the gripper and in the processing of visual information.

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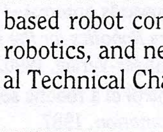

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