A FUZZY ROBOT CONTROLLER FOR THE PLACEMENT OF FABRICS ON A WORK TABLE

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Abstract: In this paper, a fuzzy system for the control of the task of laying a fabric on a table via a robot is introduced. The task of laying is investigated and the parameters affecting the appropriate guiding of the fabric are identified to formulate the rule base for the fuzzy control system, which is tuned experimentally. The fuzzy control system formed is then verified by testing the laying of fabrics with different characteristics than the ones used in the formulation of the rule base. The conclusions drawn bring forward the future research on the advancement of robot intelligence and flexibility. *Copyright © 2005 IFAC*

Keywords: Automation, Fuzzy control, Fuzzy systems, Handling, Robots.

1. INTRODUCTION

In the apparel industry, the placement of a fabric on top of a working table is one of the tasks included in handling of fabrics and its successful realization is essential for the cutting, sewing and other alteration operations. The fabric is a very limp object and the prediction of its behaviour is very difficult. Despite the importance of the fabric laying task, only a few researchers have investigated the employment of robots for the implementation of this task as part of the automation of the fabric handling in cloth making industry. The studies carried out for automatic laying of a piece of fabric using robots can be divided into three categories, the first category includes the approaches where the robot is combined with an auxiliary apparatus, the techniques of the second category are based on the modelling of the fabric and the methods of the third one rely on adaptive control.

The most representative techniques of the first category appeared in the literature are commented in the following. Ono, et al. (1991) presented a technique where the robot hand is assisted by a wire frame to spread a ply of fabric over a table in a proper manner. Two alternative systems have been proposed by Gunner and Taylor (1990) for the placement of fabrics onto moving surfaces, such as a conveyor. If the conveyor is faster than the robot, the piece of fabric is fed onto the conveyor in the direction of the travel and held, whereas if the conveyor is slower, the handling device is used to pull the fabric over the conveyor in the direction of its travel. Two other strategies have been planned by Paraschidis, et al. (1995) for laying a fabric, one by using the edge of the work table, and the other by dragging the fabric over the table. In the first case, artificial vision is used for the identification of the fact that the whole of the material is on the table and that it has reached the desired final position, and in the second case for the identification of the free rear edge of the material in order to track its position while the material moves. Such approaches lack flexibility and/or demand large working space.

A study that relies on fabric modelling has been presented by Eischen and Kim (1993), where the folding process is simulated and the results obtained using the fabric model were compared with the experimental ones. It was suggested that the minimization of the constraint reaction force during the placement operation would optimize the folding task. Despite their good results, the presented models are unsuitable for on-line control due to their high computational cost.

The technical issues associated with the acquisition, placement and folding materials with mechatronic devices and machines were discussed by Paul (2004). He presented a system, where the robot with closed loop vision feedback places and folds a two-dimensional fabric piece onto itself in half. The error measurements from the vision system are used to create an iterative fabric manipulation scheme. The manipulation trajectory scheme adapts to changing fabric parameters, surface friction, and desired folding speeds. The main drawback of this approach is that too many iterations are needed to complete the task.

In this paper, an innovative approach based on fuzzy logic is presented that considers the fabric properties and the progress of laying, and suggests an appropriate handling scheme. Laying experiments were carried out for a set of fabrics. The data gathered through these experiments were used to form a system predicting an appropriate path for the end-effector of a robot. The feedback of the proposed control system is based on standard robot joint variable measurements. Since it is not necessary to use additional sensors such as expensive vision systems, the proposed approach keeps the cost of the system low. The resultant system is tested for other types of fabric and conclusions are drawn from the results.

2. PLACEMENT OF FABRICS

The term “fabric” covers a wide field of limp objects with a great variety of structures and raw materials. The inner structure of a fabric results in very low bending stiffness, which produces a very compliant behaviour that makes its handling a very difficult task, even for workers with high dexterity. It is obvious that the robot handling of fabrics presents even higher difficulty. This is the reason for the little progress in the automation of the apparel industry. In this study, the robot control for the fabric laying is based on the fuzzy set theory.

Fuzzy control systems exhibit good behaviour under known and unknown models and conditions. The fuzzy systems can easily alter their parameters to meet the new needs and are unaffected by small changes in the environment. These traits, improve the repeatability, the flexibility, the adaptability and the robustness of the system which are essential for the successful application of a process in the industry. Another advantage of fuzzy systems is their very low computational cost making them suitable for on-line applications.

Fuzzy systems are more suitable than neural networks for robot control in the placement of fabrics since the necessary initial knowledge is available from long human experience. In cloth making industry this is a very common task and almost everyone has handled fabrics in his lifetime. A priori linguistic knowledge can be easily gathered from human expertise in a systematic manner for a good initialisation of the system, which ensures the convergence and increases its speed. Taken this into account and the clear physical meaning of the parameters of fuzzy systems, these parameters can be adjusted manually with relatively little experimental work, which is impossible in the case of ANN. The greatest advantage of ANN is their training capability, but if the fuzzy system is properly structured it can adopt training, in the form of a neuro-fuzzy system. In this case, these manual adjustments will be used for the benefit of the convergence which cannot be exploited by ANN.

2.1 Fabric Manipulation.

The successful placement of a fabric on top of a work table has to be precise and free from wrinkles. It is important to maintain the positional precision during the entire task and not only at the final position of the fabric, since this ability of the robot will constitute the basis for our future work regarding the folding of a piece of fabric. The path of the edge of the fabric, which is restrained to the end-effector of the robot, is determined in order to achieve the desired precision. In the laying task, the path of the robot hand depends on the properties and the geometry of the piece of fabric. The edge of the fabric attached to the end-effector is not allowed to rotate with respect to the hand. The starting orientation of the hand is vertical, with the fabric hanging straight down. Then the orientation of the end-effector changes following a specific curve until it becomes horizontal at the end of the path.

As it is shown in Fig. 1, all the possible paths of the robot hand holding the one edge of the fabric being laid are confined by two extreme cases, the quarter circle (a) and the straight line (b), corresponding to

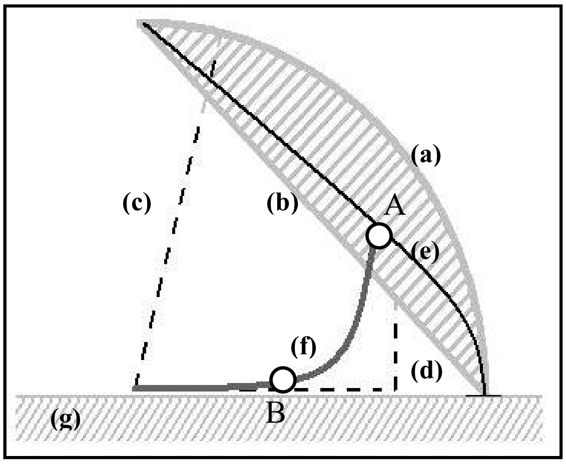

Fig. 1. Domain of possible paths.

fabrics with infinite (c) and zero (d) bending rigidity respectively. The first piece of fabric behaves as an undeformable sheet, thus the appropriate path of the robot hand is a quarter circle, with a radius equal to the length of the fabric. For the second case, where the fabric behaves like a chain, the appropriate path is the segment straight line defined by the two extreme positions of the robot hand motion.

The results of our experimental work revealed that the shape of the appropriate path (e) for laying of an arbitrary fabric (f) depends mainly on the material's rigidity, the weight per unit area and the length of the fabric from the tip A of the end-effector to the point B where the fabric touches the table (g), which in the following is called "free" length.

The free length is given indirectly with adequate accuracy for a fuzzy control system, as the ratio of the remaining path to the entire path and is called path ratio. Thus, the difficult task of measuring the free length is avoided. The bending stiffness is a property that is related to the rigidity and the weight per unit area of the fabric. The method used for the indirect measurement of the bending stiffness of fabrics was presented by Cassidy, et al. (1991). According to this suggestion, the fabric is allowed to fold back on itself and a loop forms at the fold, then the resultant loop height is measured in mm. In the following, this measured height will be referred to as bending stiffness.

Since the pieces of fabric that are examined in this paper are of constant length (200mm), the properties that are finally taken into consideration for the determination of the appropriate path are the bending stiffness and the path ratio. In return, the path is given as a set of numbers y each corresponding to a path ratio. The variable y represents the closeness of the path to the straight line and the position for the current path ratio is given by the linear interpolation between the straight line (s) and the quarter-circle (c).

$$p = ys + (1 - y)c \tag{1}$$

2.2 Fuzzy System.

In the development of a fuzzy control system, the first task is the knowledge acquisition. The knowledge for this study was in the form of experimental data and observations made during the realization of laying experiments. Nine fabrics presented in Table 1, with bending stiffness varying from 8 to 33mm were used and the appropriate paths of the end-effector were determined by trial and error. This knowledge, which is summarized in the form of linguistic rules, is employed for the formulation of a fuzzy system that guides the end-effector of the robotic manipulator. In summary, this knowledge can be given by the following two propositions:

"The greater the bending stiffness, the closer the path to the circle, while the lower the bending stiffness, the closer the path to the straight line."

"The greater the free length, the closer the path to the straight line, while the lower the free length, the closer the path to the circle."

Based on these propositions a fuzzy system was created, with two inputs, the path ratio (x_1) and the bending stiffness (x_2), and one output, the closeness to the straight line (y). For the variable path ratio, the universe of discourse is defined in the region (0, 100). For the variable x_1, three linguistic values are defined, S, M and L, corresponding to Small, Medium and Large path ratio. For the variable bending stiffness, the universe of discourse is defined in the region (0, +∞). The range of the bending stiffness of fabrics used by the apparel industry is between 5 and 35mm. For the variable x_2, four linguistic values are defined, VS, S, L and VL, corresponding to Very Small, Small, Large and Very Large bending stiffness. For the output of the controller y, the universe of discourse is defined in the region (0, 1), with Six linguistic values, AC, VCC, CC, CL, VCL and AL, corresponding to Almost Circle, Very Close to Circle, Close to Circle, Close to Line, Very Close to Line and Almost Line. The rule base is composed of linguistic rules and their number is 3x4=12. Table 2 shows the Fuzzy Associative Memory of the system where the rule confidence is equal to one.

The Gaussian and Singleton membership functions are used for the inputs and the output of the system respectively, so that the formed system will be susceptible to neuro-fuzzy training for future work. The system is chosen to have a centre average defuzzifier and product-inference rule given by eq. (2), where $f(\underline{x})$ is the output y of the system, $\underline{x}$ is the input vector (x_1, x_2)^T, $\bar{y}^j$, $\bar{x}_i^j$ and σ_i^j are the support of fuzzy singleton and the centre and standard deviation of the Gaussian membership function of the jth rule and of the ith input respectively. The membership functions of the variables x_1, x_2 and the output y are presented in Fig. 2, 3 and 4.

Table 1 Fabrics used for the formation of the fuzzy system

Fabric	Type	Structure	Bending Stiffness (mm)
1	knitted	Rib 1x1	8
2	knitted	Pique	13
3	knitted	Interlock	16
4	knitted	Fleece	18
5	knitted	Footer	19
6	knitted	Rib 1x1	19
7	woven	1/1	29
8	woven	corduroy	33
9	woven	2/2	33

Table 2 Fuzzy Associative Memory (FAM) of the fuzzy system

x_2	x_1		
	S	M	L
VS	AL	AL	AL
S	VCL	VCL	VCL
L	VCC	CC	CL
VL	AC	VCC	CC

The $\bar{x}_i^j$ and σ_i^j parameters shown in Table 3 were chosen taking into account that the sum of rules which are triggered by every input vector $\underline{x}$ is greater than the unit, and the rules' activation surface is kept as close to the horizontal plane as possible, as it is illustrated in Fig. 5. As a result, triggering of the rules has a maximum to minimum ratio of 1.25. The $\bar{y}^j$ parameters were manually fine-tuned based on the experimental procedure, where the 9 fabrics shown in Table 1, with a variety of characteristics are laid on the work table. The resultant path combination proportion surface is illustrated in Fig. 6.

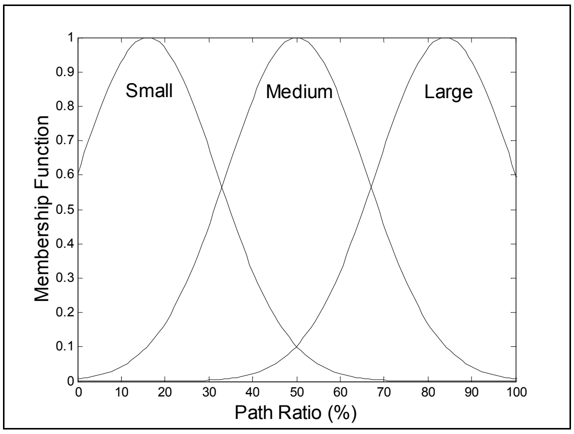

Fig. 2. Membership functions of the path ratio.

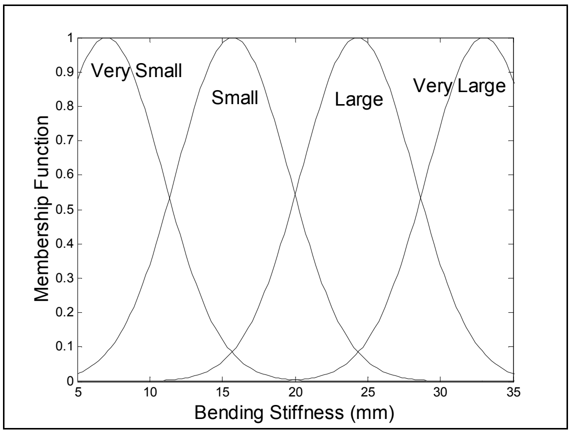

Fig. 3. Membership functions of the bending stiffness.

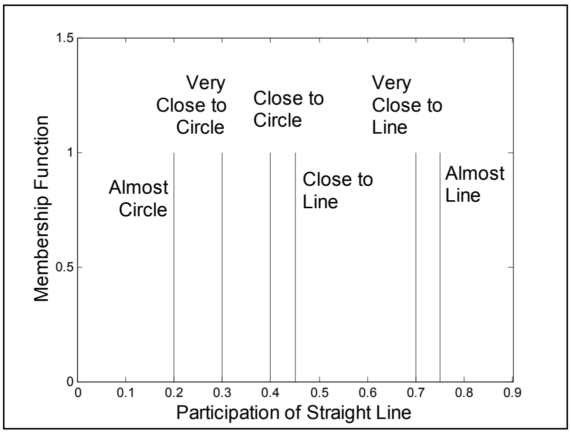

Fig. 4. Membership functions of the output.

Table 3 The final fuzzy rules' parameters

l	$\bar{x}_1^l$	σ_1^l	$\bar{x}_2^l$	σ_2^l	$\bar{y}^l$
1	16	22.5	7	5.5	0.75
2	50	22.5	7	5.5	0.75
3	84	22.5	7	5.5	0.75
4	16	22.5	15.7	5.5	0.7
5	50	22.5	15.7	5.5	0.7
6	84	22.5	15.7	5.5	0.7
7	16	22.5	24.3	5.5	0.3
8	50	22.5	24.3	5.5	0.4
9	84	22.5	24.3	5.5	0.45
10	16	22.5	33	5.5	0.2
11	50	22.5	33	5.5	0.3
12	84	22.5	33	5.5	0.4

$$f(\underline{x}) = \frac{\sum_{l=1}^{M} \bar{y}^l \left(\prod_{i=1}^{n} \exp\left(-\left(\frac{x_i-\bar{x}_i^l}{\sigma_i^l}\right)^2\right)\right)}{\sum_{l=1}^{M}\left(\prod_{i=1}^{n}\exp\left(-\left(\frac{x_i-\bar{x}_i^l}{\sigma_i^l}\right)^2\right)\right)} \quad (2)$$

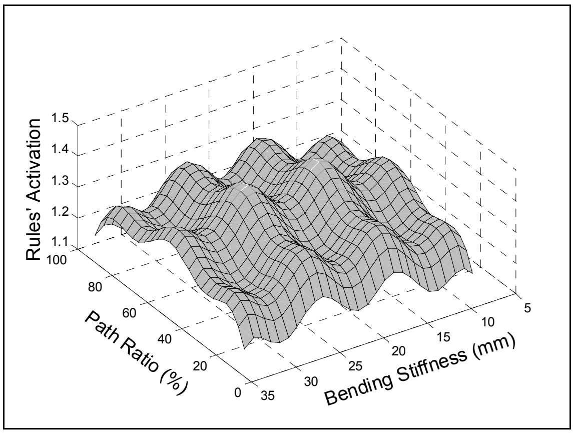

Fig. 5. The rules' activation surface.

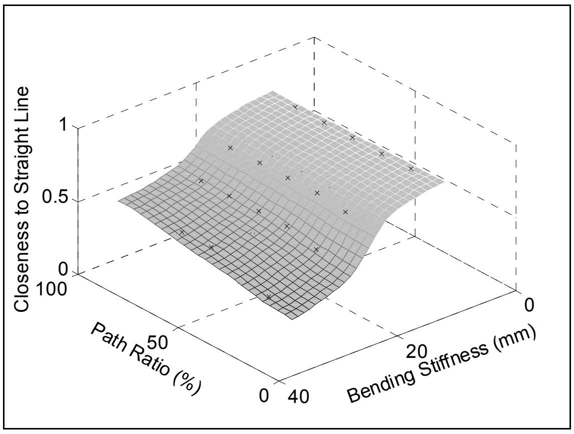

Fig. 6. The path combination proportion surface.

2.3 Experimental verification.

The fuzzy system formed was tested for the 20 different fabrics shown in Table 4, including the 9 fabrics used for the formulation of the fuzzy rules and sets, and 11 additional fabrics of various bending stiffness. For each test carried on, the success (S) or failure (F) is indicated and the maximum position error that occurred is shown. A test is considered as successful when the maximum position error does not exceed 3mm.

Since the scope of this study is the determination of the appropriate path of the end-effector and because some fabrics tend to curl at the start of their laying, the experiments started from a position where the fabrics were already in contact with the table. The fabrics at that starting position were straightened by hand so that their edge in contact with the table being at the correct position and free from curls.

Fig. 7 presents six instances of the laying of a very limp fabric, the first in Table 4, following the appropriate path derived from the fuzzy system. The desired position of the free edge of the fabric is defined by the third of the five equidistant straight line segments. The segments are 10mm apart. As Fig. 7 illustrates, the free edge of the fabric almost coincides with the desired line during the laying of the fabric and the final error is within the acceptable limit. In Fig. 8, the laying of a stiff fabric, the 14th in Table 4, is shown. A successful laying is also achieved. Slight deviations, up to 1mm, observed in respect to the correct position are also due to probable misalignments regarding the attachment of the fabric on the end-effector. Similar behaviour is exhibited by the rest of the samples used for the verification of the system, except for the 20th one.

Fig. 9 demonstrates the behaviour of a fabric sample, the last presented in Table 4, with a bending stiffness of 100mm, which is well outside the domain that the fuzzy system was formed and tuned to operate. As a result, the system fails to predict a proper path for the end-effector to follow, and thus a maximum error of 9mm is observed during its laying.

Fabrics sharing the same bending stiffness, and thus expected to behave similarly under the appropriate path given by the fuzzy system, presented slight differences during their laying. From this result, it can be concluded that the bending stiffness is not enough to fully characterize the fabric for the laying process and therefore additional properties should be considered too for the fuzzy system to predict an appropriate end-effector path. Errors might yet occur due to air flow, vibrations, etc., so a control system should be created to compensate these effects, taking into consideration both the properties of the fabric, the path ratio and the positional error.

Even though the studies that have been carried out in the field so far do not state the time needed for the fulfilment of the task, it is expected that those that are based on a model of the material (Eischen and Kim, 1993) or follow iterative methods (Paul, 2004) are time consuming. Those studies that present fast laying schemes (Gunner and Taylor, 1990), (Ono, et al., 1991) and (Paraschidis, et al., 1995) are based on the utilisation of other apparatuses which means very low flexibility and adaptability. Maximum and acceptable errors are not stated in either of these studies, and thus a comparison is impossible. The proposed system is both fast with a very low computational cost, and flexible since it can cope with a great variety of materials and sizes limited by the range of samples used for its formation.

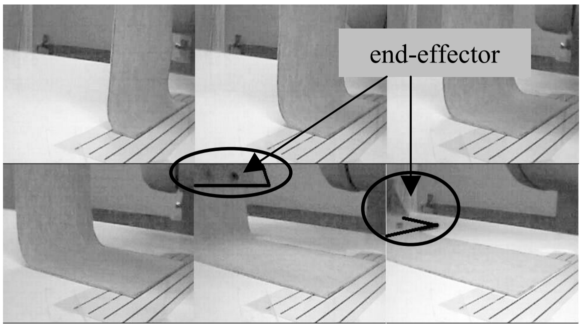

Fig. 7. Laying a very limp fabric.

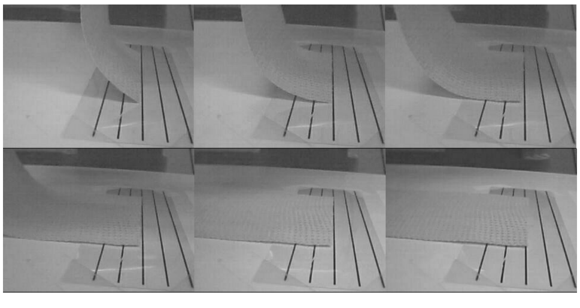

Fig. 8. Laying a stiff fabric.

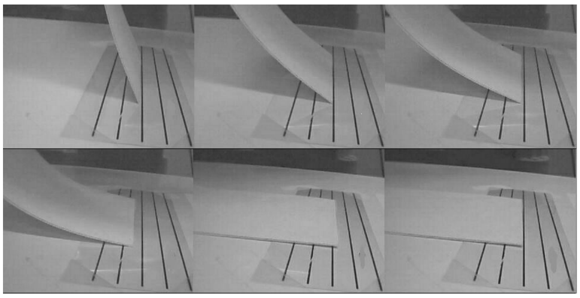

Fig. 9. Laying a very stiff fabric.

3. CONCLUSIONS

In this paper, the design of a fuzzy control system was presented for defining the appropriate path of the robot hand for the laying of fabrics. The system was tuned experimentally and then tested for a variety of materials.

The precision exhibited during the laying of the fabrics, after predicting their appropriate path through the designed fuzzy system, suggests that this approach is promising and could lead to a low cost system applicable to the apparel industry. This artificial intelligence scheme has the potency to compensate those characteristics of fabrics that prevent the handling of fabrics automation in the apparel industry.

The designed system results in a successful laying for the fabrics within the domain in which it was tuned but is unable to cope with fabrics of very high bending stiffness. The solution to this problem is the employment of an even wider range of material for the tuning of the system. Improvements should also be made regarding both the accuracy of the given system and the fabric properties received as inputs to the system, such as the weight per unit area and the length. A clustering algorithm should be used to smooth the experimental data, and a neuro-fuzzy training algorithm should be incorporated to automatically fine-tune the system, instead of human operators.

Table 4 Fabrics employed in the experimental verification

Fabric	Bending Stiffness (mm)	Verification Result	Maximum Error (mm)
1	8	S	1
2	12	S	1
3	13	S	1
4	13	S	1
5	14	S	1
6	16	S	1
7	17	S	1
8	17	S	1
9	18	S	1
10	18	S	1
11	19	S	1
12	19	S	1
13	19	S	2
14	19	S	1
15	23	S	1
16	24	S	2
17	29	S	1
18	33	S	2
19	33	S	1
20	100	F	9

An on-line fuzzy system using visual sensing should be developed to correct the path of the end-effector by reducing the position error of fabrics. It is under investigation whether the position error can be predicted prior to its occurrence, and thus to be avoided by monitoring the shape of the fabric during its laying.

Clearly, further research is needed for the successful implementation of robots in the apparel industry. The use of artificial intelligence methods to control the robots promotes the development of the next generation, innovative intelligent robots.

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