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A knowledge-based system for the conceptual design of grippers for handling fabrics

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Abstract

The paper presents a knowledge-based system (KBS) for the conceptual design of grippers for handling fabrics. Its main purpose is the integration of the domain knowledge in a single system for the systematic design of this type of grippers. The knowledge presented, in terms of gripper, material and handling process, are classified. The reasoning strategy is based upon a combination of a depth-first search method and a heuristic method. The heuristic search method finds a final solution from a given set of feasible solutions and can synthesize new solutions to accomplish the required specifications. Details of the main features of the system are given, including its ability to take critical design decisions according to four criteria, weighted by the designer. The knowledge-based system was implemented in the Kappa P. C. 2.3.2 environment. Two examples are given to illustrate some critical aspects concerning the KBS development, to explain the operation of the proposed searching heuristic method, and to show its effectiveness in producing design concepts for grippers.

Keywords: Knowledge-based Systems; Design; Fabrics

1. INTRODUCTION

A gripper is a key component of a robotic workcell. Correct design of a gripper is extremely important for the success of a robotic handling task and can reduce the cost of the workcell. Design of grippers is an engineering task where many factors have to be considered for obtaining successful results. Any computational design tool, and more specific, a knowledge-based system (KBS) containing up-to-date design knowledge would contribute toward this direction.

According to Dym (1994), recent advances in the field of artificial intelligence (AI), particularly symbolic representation and related problem-solving methods, offers significant opportunities to clarify and articulate concepts of design so as to lay a better framework for design research. Design activities encompass a spectrum from routine design, through variant design, to truly creative design of new artifacts. While routine design is possible to be computable, it is difficult to model creative design. According to Green (1992), computers, currently, play two roles in design. One set of tools aids in the final drafting of the specifications and the second in analysis. Both of them are used long after designers have made their major decisions, and cannot recognize why a candidate design failed or what changes are required. He coined the term "knowledge-aided design" (KAD) to contrast the current computer-aided design (CAD) tools. While CAD tools are used only after the major design decisions have been made, KAD systems operate at a much earlier stage in the design process, when engineers make the major—and more critical—decisions.

A few papers concerning CAD of grippers have appeared in the literature. Pham and Tacgin (1992*b)* developed a hybrid expert system for the detailed selection of robot grippers. The main objective of the system is to assist the user in choosing suitable grippers for industrial tasks varying from a simple pick-and-place operation to more sophisticated processes such as mechanical assembly. The system consists of two parts dealing with preliminary and detailed choices. In both parts, the Bayesian uncertainty technique is used to rank the proposed items and an adaptive learning algorithm is provided to capture the user's expertise during a consultation.

In the preliminary choice section, suitable gripper types are suggested according to the general requirements of the

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user. The grippers available at this stage are categorized into three groups namely, clamping, flexible, and single surface grippers (Pham & Tacgin, 1992*a*). A clamping gripper holds a component by applying, externally or internally, pressure to more than one face of the latter. Two-jaw and three-jaw grippers are the most common types of this group. The term "flexible" refers to the ability of a single gripper to adapt its form according to the shape of the component to be grasped. The flexible gripper types used are multifingered, soft, bladder and adjustable jaws grippers. Single-surface grippers are selected in situations where only one surface of the workpiece is available for gripping and they are categorized as magnetic, vacuum, and adhesive grippers. The detailed selection of the gripper is made from two commercial available catalogs (Pham & Tacgin, 1991), using information of the robot, the component to be handled, and the exact task to be accomplished.

Heilala et al. (1992) developed a systematic mechatronic design concept for industrial grippers that speed up and improve the design of them. The design process starts with the clarification of the task. The specifications of the problem are found through the creation of a hierarchical list, which contains significant problems concerning the application. This list is refined and after the evaluation of the critical factors leads to the final specification list. In the conceptual-design phase, the gripper needs to be conceptualized, sensors and control systems have to be taken into consideration, as well as the robot itself.

There are two major motivations for the development of the present KBS: The integration—for the first time—of the available knowledge in a single system, and the systematic design of the grippers for handling fabrics. The design process ends with the conceptualization of the gripper (operating principle, control method, type of gripper, etc.). The resulting concept is not simply a selection among commercially available grippers, but, when required, a combination of operating principles and handling techniques for a new gripping concept. Additionally, the system aims toward the determination of the auxiliary equipment of the gripper, a task that has not been discussed in the papers previously mentioned. The final solution is chosen from a set of feasible solutions by applying operating criteria weighted by the designer.

Next, a detailed presentation of the knowledge used is given. This knowledge refers to the various concepts of grippers and the relevant features of the fabrics, as well as to the handling process itself. The KBS was built in a Kappa P.C. 2.3.2 environment, a commercially available expert-system shell. In addition, techniques for the search of the solutions and a list of criteria for the final selection from a set of solutions have been introduced. Two examples are also presented to show the efficiency of the KBS. The concluding remarks refer to the usefulness of the system that provides "expert-quality" performance and acts as an advisor when engineers have to take critical decisions concerning the design of grippers.

2. THE DESIGN OF GRIPPERS—THE DOMAIN KNOWLEDGE

Generally, the design process follows three main steps: specification development/planning phase, conceptual design, and detailed design (Ullman, 1992). The goal of the specification development/planning phase is to understand the design problem, generate engineering requirements, and establish targets and plans for the design. Understanding the

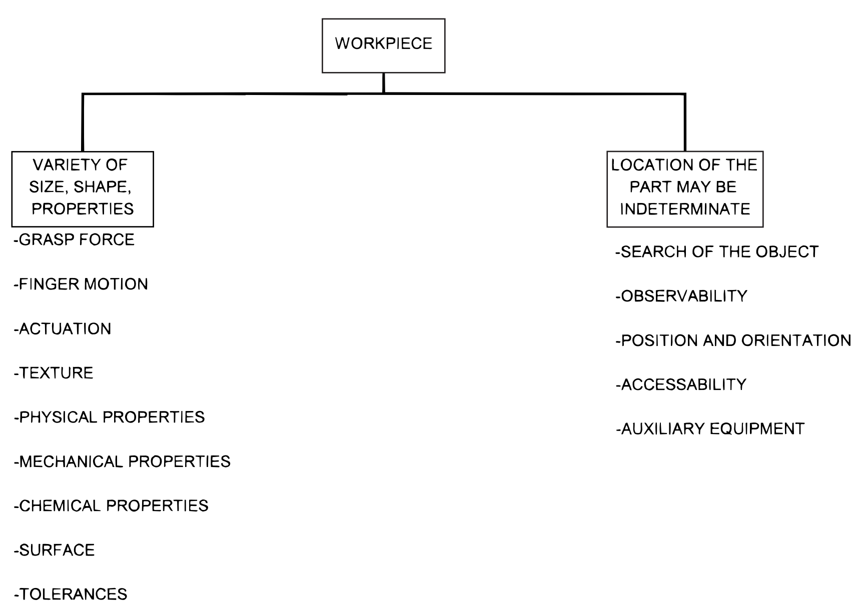

Fig. 1. Workpiece includes detailed parameters that must be considered in design.

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design problem is not an easy task because most design problems are ill-defined. When this task is accomplished, then a plan for the next phases of the design process must be established. Often, the development of the specifications will determine how the design problem can be decomposed into smaller subproblems. The results of the specification development phase are used to generate and evaluate concepts for the product in conceptual design phase. The requirements of the task that the product must accomplish serve as a basis for developing a functional model of the design, which leads to the generation of concepts from functions. Functional decomposition may occur, which leads the problem in a more manageable form. The concepts that are generated also have to be evaluated for their feasibility, or compared to choose the best one. After the concepts have been generated and evaluated, the best is further processed to produce a final design.

The design process of grippers for handling fabrics follows the same steps. For the KBS under consideration, focus is given to the first two steps of the design process. In the first step, the essential specifications are stated that have to be fulfilled to obtain the desired operation. One way to systematically search for the specifications is to create a hierarchical list of all the significant problems concerning the application (Heilala et al., 1992). When all the potential problems are listed, as a result of the evaluation of the critical factors, the refinement of final specification list for preliminary design is completed. The clarification of the problem is described in terms of the workpiece, the handling process, and the gripper itself. In Figures 1–3, details are given concerning the attributes of these factors. This problem hierarchy belongs to a general mechatronic approach for designing grippers. Some necessary modifications must be made to the general approach due to the nature of the task that grippers perform (for example, radiation is not taken into consideration).

Because design of grippers is a relatively new design field, and there are not many working robotic cells for flexible materials, it was proved difficult to find experts in the field. Therefore, the knowledge used to build the present KBS was acquired mostly from papers and handbooks. Additionally, the available literature was searched to find as much as possible information about the design and manufacturing of grippers.

2.1. Knowledge about fabrics

The workpiece is the most important factor for the gripper design. It affects the structure and the function of the gripper. The particular size, shape, and mass of the workpiece determine the final solution. There are, however, cases where the position and orientation of the workpiece are uncertain and, as a consequence, the determination of the final solution becomes a difficult task.

Fabric specifications can be categorized into two groups: properties and characteristics. A property is a static physical dimension and, a characteristic is the reaction of a fabric when a force is imposed upon it. The properties and characteristics of the fabrics are shown in Table 1, according to Solinger (1988) and Hudson (1988). Elongation, elasticity, and shrinkage are examples of characteristics, but weight is a property of fabrics. The properties, the hand, and the utility characteristics are more useful for the design of the grippers than the style, durability, and product production characteristics that mainly correspond to the apparel producers. Some of them are general and some are specific for

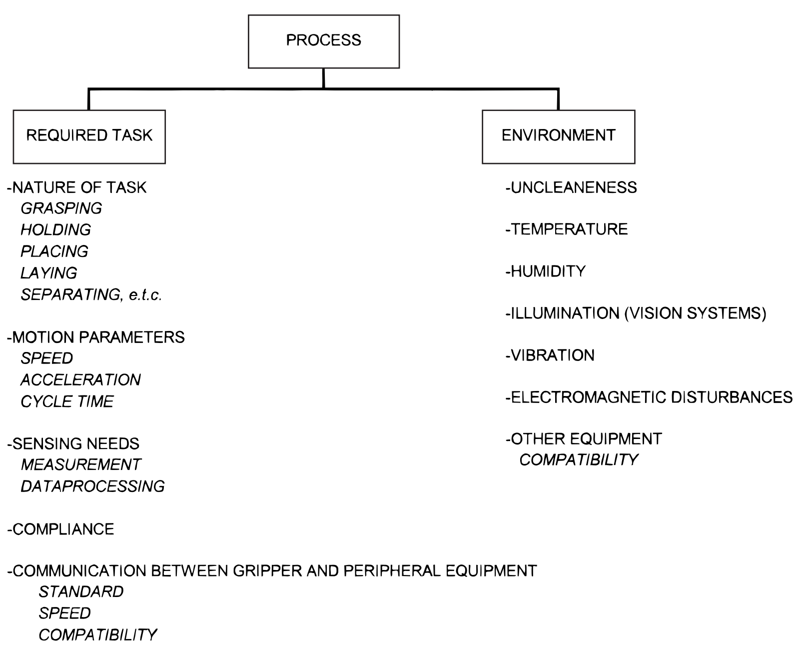

Fig. 2. Process includes detailed parameters that must be considered in design.

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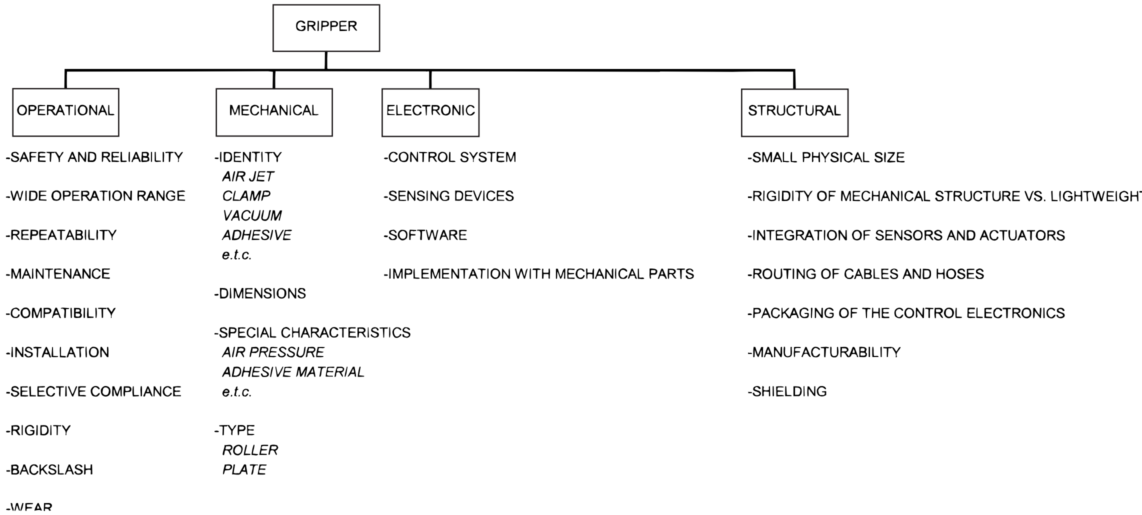

Fig. 3. Characteristics and parts of gripper.

particular grippers. For example, porosity is a vital factor when pin grippers are used because they may damage delicate fabrics. When vision sensors are used the color of the fabric has to be taken into consideration.

2.2. Knowledge of the handling process

The type of handling process determines the design parameters to be considered. Formally, it is expressed through the task to be implemented and the environment within which the task takes place. Both the task and the environment are considered as external design parameters.

Dlaboha (1981*a, b)* stated that apparel plants may benefit from the use of robots in a variety of operations, such as destacking, folding, die cutting etc. All the operations can be further divided in more simple subtasks, namely:

- separation;
- picking;
- placing;
- applying tension; and
- assembling (for example the superposition of two panels).

For example, a sewing process includes an assembly task and an applying tension task. In some cases, environment is a vital factor. Dust is undesirable in grippers with adhesives. Relative humidity is desirable in freezing grippers and affects the electrical properties of the material. Vibrations in the task of destacking releases the clinging edges of the materials.

Table 1. *Properties of fabrics*

Properties
Fiber or filament: Type, size, length.
Yarn: Diameter, twist, weight or size count, fiber content for mixed yarns, ply.
Weight: Ounces per square yard or yards per pound.
Thickness: Vertical depth.
Fabric structure: Woven fabrics; weave type, warp and filling yarn count per linear inch. Knitted fabrics; knit type, wale, and course count per linear inch.
Nonfibrous matter: Residual processing chemicals remaining in the fabric. Percentage of weight per total fabric weight.
Finishes: Chemicals and mechanical effects applied to the woven fabric to yield or enhance style durability, and/or utility values.
Fabric width: The length of the filling or course.
Color: hue, value, and intensity.
Fabric density: Weight per unit of volume.
Surface contour: The geometric dimension of the surface plane.

2.3. Knowledge about grippers

The gripper, which is the design goal, presents some operational and structural attributes and includes mechanical and electronic parts. Usually, grippers cooperate with auxiliary equipment, which has to be specified, too.

Figure 4 illustrates the main handling techniques, which are divided into the following three classes (Taylor, 1995):

1. Mechanical surface, where the material is clamped or pinched between gripper finger to give high frictional holding forces.
2. Intrusive, where pins are fed into the surface or body of the material and then moved to lock it into place.
3. Surface attraction, including the use of adhesives/vacuum.

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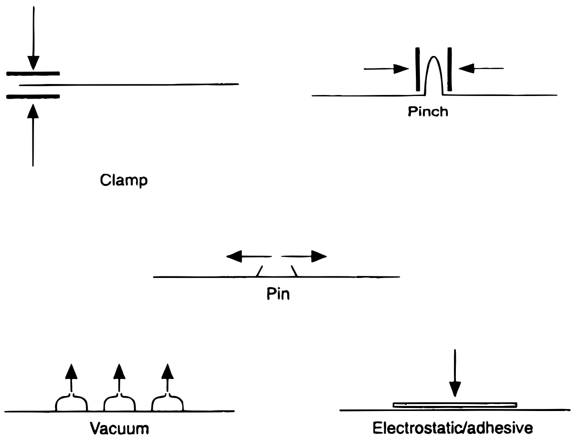

Fig. 4. Gripper techniques.

It is obvious that the choice of one of those techniques depends on some properties of the material and its location.

Grippers can be categorized, also, by considered their operating principles. These categories are:

1. Pinching grippers (Monkman, 1993).
2. Clamping grippers (Eiichi et al., 1989; Karakerezis et al., 1994*a*, 1994*b*; Karakerezis, Doulgeri, Rizzi, et al., 1994; Karakerezis, Ippolito, et al., 1994; Paraschidis et al., 1995).
3. Air-jets (Kemp et al., 1986).
4. Pin grippers (Parker et al., 1983).
5. Brush grippers (Velcro).
6. Vacuum/pneumatic grippers (Parker et al., 1983; Kolluru et al., 1995).
7. Electrostatic/magnetic grippers (Monkman, 1995; Monkman et al., 1989).
8. Adhesive grippers (Parker et al., 1983; Monkman & Shimmin, 1991*a*, 1991*b)*.
9. Freezing grippers.

The difference between these two classifications is that the first is based upon the way that the gripper approaches the fabric and the second one by the working principle of the gripper. The (1)–(3) operational principles, called impactive, are used in the mechanical surface technique. The (4)–(5) operational principles, called ingressive, are used in the intrusive technique. The (6)–(9) operational principles, called astrictive (6–7) and contigutive (8–9) are used in the surface attraction technique.

According to Taylor (1994), the main factors to be considered, in addition to weight, are:

- Impactive: Fabric bending stiffness, friction between gripper, and fabric surface.
- Ingressive: Fabric stiffness, possible damage to delicate materials.
- Astrictive: Fabric molecular structure, surface texture, and flatness.
- Contigutive: Adhesive replenishment/cleaning, secondary removal mechanism, heating/cooling cycles.

The control strategies that are used to handle fabrics can be classified into five categories, (Gershon, 1993):

- rigidization refers to any technique that temporarily transforms the flexible material to a rigid object;
- model-based trajectory planning refers to the use of a mathematical model of the flexible sheet, its mechanical behavior, and the task, to plan off-line a suitable robot motion that will perform the task successfully;
- feedback-control strategies refers to the dynamic use of a sensor signal in a control loop during the performance of a dynamic manipulation task;
- sensor-based strategy, which is a reactive sequence of elementary sensor-driven motions that reduce uncertainty in the state of the sheet; and
- sensor-less strategy, which is a predetermined sequence of elementary motions that are designed to reduce bounded uncertainty without sensing the state of the fabric.

The correct presence of a fabric panel can be detected by a number of different sensing techniques, such as:

- optical: reflective/through infrared;
- mechanical: detect limit of jaw movements;
- air flow: detect pressure drop of air flow.

3. DEVELOPMENT OF A KBS FOR THE DESIGN OF GRIPPERS

3.1. Structure of the system

The representation of the design knowledge can be made using logic, semantic networks, object-oriented programming (OOP), production rules, or a combination of these methods (Winstanley, 1991). For the present case, OOP was chosen for two reasons: The first one is that by using OOP the rules of the inference engine are easily integrated with the conventional methods. Conventional methods will be used, mainly, for calculations in a future module of the system that will perform detailed design. Second, the software used for the implementation of the KBS is object-oriented.

Five classes were used to represent the knowledge in the system. Each class contains characteristic slots, such us operating principles of the gripper, control strategy, etc. The classes and the slots are shown in Table 3. The slots for Gripper and Control are taken from Section 2.3. The most informative attributes for the Material, according to Taylor (1994), are taken from Tables 1 and 2. In addition, the environmen-

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Table 2. *Characteristics of fabrics*

Characteristics
Hand: Thickness compressibility, plane compressibility, elongation, elasticity, torsion, malleability, flexibility (self-flex, resistance flex, maintenance flex, reflex), resilience, gravity drape, gravity sag, gravity elongation.
Visual: The changes in color when either the light or fabric is moved.
Utility: Air permeability, heat transmission, light permeability, moisture transmission, radioactivity transmission, water permeability, color fastness, crease resistance, crease retention, crock resistance, dimensional stability, felting, fusing, mildew resistance, moisture absorption, moisture retention, pilling, scorching, soiling, shrinkage, static electricity, yarn slippage.
Durability: Abrasive strength, bursting strength, corrosive strength, dry cleaning durability, fire resistance, launderability, moth resistance, radiation absorption strength, tearing strength, tensile strength, yarn severance.
Product production working: Coefficient of friction, Sewed seam strength, sewed seam slippage, sewing distortions, yarn severage, bondability strength, die moldability, pressing moldability.

tal factors that affect the design of grippers and taken into consideration are shown in Table 3.

Six rule sets were used for obtaining feasible solutions. The number in parentheses show the number of rules in the corresponding rule set. These sets are:

Table 3. *Classes and slots*

Class	Slots	Values
Gripper	Operating Principle	Freezing, clamp, velcro, pin, pinch, adhesive, electroadhesive, vacuum, airjet
	Power	High, medium, low
	Setup	Initial, readjustments
Control	Strategy	Sensor-based, sensor-less, feedback, rigidization, model-based
	Sensing	True, False
Material	Density	Low, medium, high
	Identity	Cotton, velvet, linen, silk, lace, leather etc.
	Porosity	0–100%
	Molecular Weight	Low, medium, high
	Status	Free, free from the edge, free from above
	Surface	Rough, smooth
	Texture	Woven, knitted
	Thickness	0–5 mm
	Weight	Low, medium, high
Gripping process	Task	Separation, apply tension, realizing, picking, assembly, placing
Environment	Dust	True, False
	Temperature	Low, medium, high
	R. H.	0–100%

1. Rules for the operating principle of grippers (41), for example,
   If Task is Placing And Status of Material is Free Then Gripper Operating Principle is Adhesive.
2. Rules that represent the design constraints (8), for example,
   If Porosity of material is more than 30% Then Gripper Operating Principle is Not Vacuum.
3. Rules for the type of the particular gripper (5), for example,
   If Task is Separation And Gripper Operating Principle is Adhesive Then Type of Gripper is Plate.
4. Rules for the general characteristics of the gripper (6), for example,
   If Gripper Operating Principle is Air-jet and Status of fibers is clinged Then Power is High.
5. Rules for the control strategy (11), for example,
   If Gripper Operating Principle is Vacuum and Task is Placing Then Control Strategy is Rigidization.
   If Control Strategy is Sensor-Based Then Sensors are Needed.
6. Rules for the auxiliary equipment (6), for example,
   If Gripper Operating Principle is Velcro Then Auxiliary Equipment is Remover.

3.2. Finding the best solution—Complexity of the search method

For most of the design problems, solutions are not known *a priori*. The design is a data-driven process and the most usual inference mechanism is forward-chaining because it produces more data while trying to find one or more solutions to the problem under consideration. The steps of the process for designing grippers are shown in Figure 5. The reasoning strategy is based upon a combination of a depth-first search method and a heuristic one. After inputting the values for the required tasks and material, depth-first search method is fired with the first rule set for every task separately. The set of solutions of the first rule set, which represents operating principles of the grippers, are inputted in the second, which refines them and produces a set of feasible solutions. A heuristic search method is fired, which obtains the set of final solutions of the problem. Next, the last four rule sets are sequentially fired for every final solution and, then, produce the type of the grippers, the control strategy, and if sensing is needed, the general characteristics of the grippers and the auxiliary equipment.

Every design problem may have one or more feasible solutions. Below, a systematic process is presented that ends with the presentation of a single solution that satisfies all the required specifications for the handling process. If there is no such a operational principle, then a synthesis of the minimum number of operational principles is implemented that leads to the simplest solution. This process is described below:

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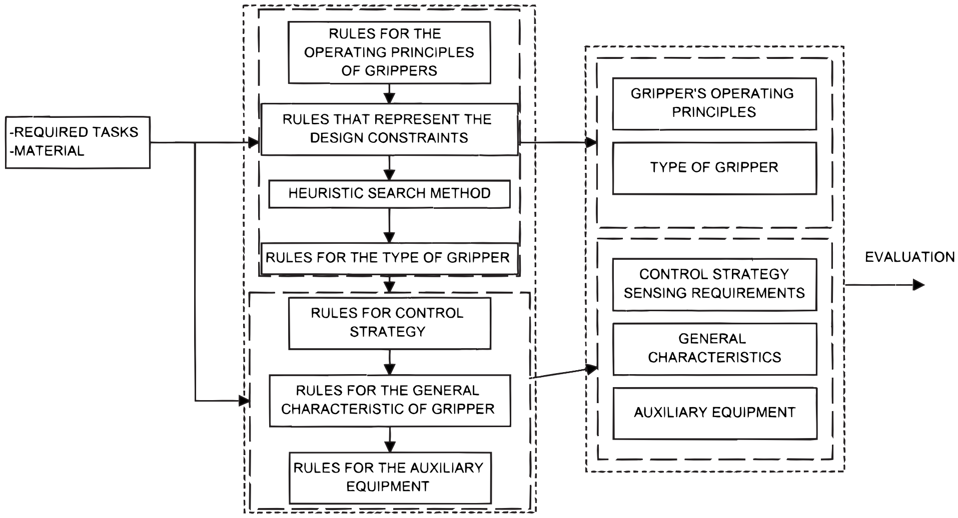

Fig. 5. Steps of the design process for grippers.

Consider a multitasking problem with **m** subtasks to be accomplished. The 1) set of rules may produce for every task from **0** to **n** feasible solutions for the operating principles of the grippers (denoted by **1**s in Table 4). Some of these feasible solutions may be constrained by the set of rules 2) concerning the material characteristics. Then, these particular operating principles are assigned with zeros. All the NULL elements of the matrix are considered as zeros. If a task is not satisfied (a row is full of zeros), then there is no solution for the problem.

Table 4 was produced after the repetitive application of the depth-first method and contains all the information about tasks and operating principles (in Table 4, the **0**s and **1**s are located arbitrarily). The principles are sorted by setting the first column the principle with the maximum number of ones. Then, a procedure starts that searches the row of the matrix in the following way:

If the first column is full of nonzero elements, then it is a feasible solution. The procedure continues until it reaches a column with at least one zero element. When that happens, it unifies this column with the next columns. If the union has nonzero elements, then it is a solution. A check is made to see whether a column does not affect the zero elements of the previous columns and if that happens, it is not taken into consideration and is rejected as redundant. The procedure continues iteratively until the last column is reached. The pseudocode of the heuristic method is shown in Figure 6. Let **A** be the matrix that is produced from the depth-first method, which contains **n** columns that represent feasible solution of grippers that partially—in the sense of not all—accomplishes **m** tasks (Step 1). This matrix is sorted by its columns (Step 2). The first column of the matrix is assigned as a possible solution, **PS**, (Step 4). If **PS** is full of ones then it is a final solution (Step 5), which is saved and the procedure continues with the next column (Step 3). If **PS** is not a final solution, then it is unified with the next column of matrix **A**, **A(:,k+i)**, (Step 6), and forms a new vector as a possible solution, **PS(L)**, where **L** is the number of iterations that produce new vectors different from the previous. Index **i** ranges values from 1 to the number of columns **n,** and index **k** ranges from 1 to the number of columns minus **i**, **(n–i)**. The vectors **PS(L)** and **PS(L-1)** are checked (Step 7). If they are found to be the same, the iteration index does not increase and the **PS(L-1)** vector is unified with **A(:,k+i)**, where **k** = 2. If **PS(L)** and **PS(L-1)** are different, the procedure goes to Step 5. The complexity of the method is shown in Appendix A.

Using additional criteria—such as reliability, speed, etc.—the designer may evaluate the feasible solutions and choose the best of them. The KBS offers four operating criteria:

- reliability;
- repeatability;
- maintenance; and
- cycle time.

The first two are characteristics that can be found in the literature. They do not reflect the final reliability or repeatability, but they can be used as an index for grippers that have the same operating principle. For example, Kemp et al. (1986) construct an Air-Jet gripper with 98% reliabil-

Table 4. *Tasks and operating principles produced by the KBS*

Task no. ↓, Principle no. →	1	2	…	n
1	1	0	…	1
2	1	0	…	0
⋮	⋮	⋮	⋱	⋮
m	0	1	…	1

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Step 1.  Production of matrix A(mxn).
Step 2.  Sorting of matrix A.
Step 3.  FOR i=1 TO (number of columns of A)
         DO:
                {
Step 4.  Assign A(:,i) as PS(0);
                k=1;
                L=1;
Step 5.  IF all elements of PS(L-1) is one
                THEN it is a solution, save it, and
         GOTO step 3.
                ELSE
                {
                  WHILE (i+k<= n)
                  {
Step 6.           Unify PS(L-1) with A(:,k+i) and
                  produce PS(L).
Step 7.           IF A(:,k+i) is redundant
                          THEN
                          {
                          k=k+1;
                          GOTO Step 6
                          }
                          ELSE
                          {
                          L=L+1;
                          GOTO Step 5.
                          };
                  };
                };
                };
```

Fig. 6. Pseudocode of the heuristic search method.

ity and Kolluru et al. (1995), a vacuum gripper with more than 99.6% reliability. The structures of these grippers are simple, and the values of their repeatability is high (100%). According to Heilala et al. (1992), repeatability is an operational factor of the gripper. Concerning the term maintenance, in the context of the present problem, it includes some special tasks, such as cleaning or changing specific parts of the gripper during its operation. For example, the adhesive grippers need to clean their pad or change their adhesive tape after a specific number of cycles (Parker et al., 1983). If maintenance is needed for a gripper, then a mark of 0.5 is given to it, otherwise this mark is 1.

Cycle time is defined as a fuzzy variable. The cycle time depends absolutely upon the manufacturer and the implemented task and as a result, there are no established standards for it. The contribution of the gripper in the cycle time is scored according to this criterion. It is difficult to create a single formula for the duration of all different tasks. It is convenient to represent it using fuzzy logic. Knowing the fastest and the slowest operation (zero time), the bounds for the fuzzy system can be created. Three subsets (high, medium, and low) are then used together with three rules that conclude about that characteristic of the gripper. The fuzzy system is Sugeno-style and the rules have the form:

IF: cycle is …
THEN: coefficient is … .

Cycle's coefficient is a crisp number, formally named as a singleton. When the cycle time is high, the coefficient is low. When the cycle time is low, the coefficient is high, and when it is medium, the coefficient is medium. The relations between the fuzzy sets and the singletons are shown in Table 5. Verification of this fuzzy system was made using the MATLAB (Gulley & Roger Jang, 1995). The membership functions for the cycle time is shown in Figure 7a and the obtained output surface is illustrated in Figure 7b.

When the solution contains more than one operation principles, then the reliability, repeatability and maintenance factors is the product of each operation principle factor. For the cycle time, all the consequences of the rules of all the operating principles are fused and defuzzified (Yen & Pfluger, 1995).

The best solution, according to the four criteria, is obtained by weights that are defined by the designer. The set of solutions is represented by a set of degrees and the solution that has the higher degree is the best. These degrees are given by the formula:

$$\text{degree} = \frac{\sum w_i f_i}{\sum w_i},$$

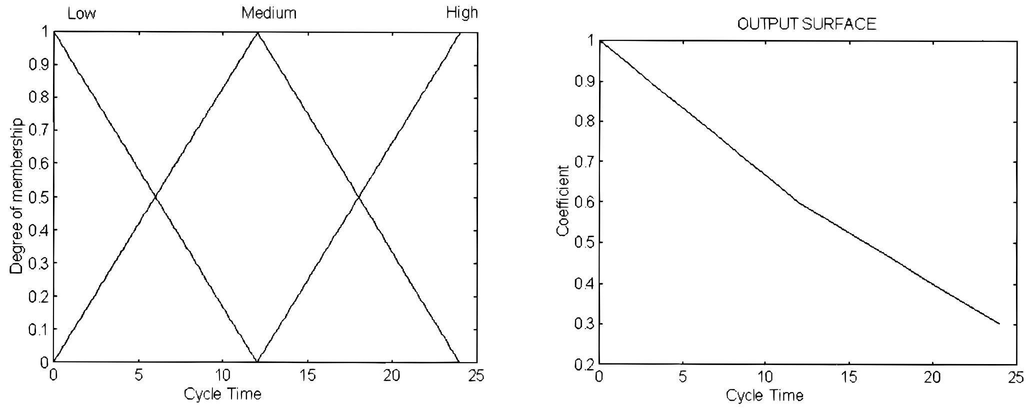
where w_i is the weight of the ith criterion and f_i is the factor that corresponds to the ith criterion of the particular gripper.

4. EXAMPLES

Below, two examples are given. The first one refers to a simple task, while the second refers to a complicated one that, however, can be divided into simple tasks.

Table 5. *Relations between the fuzzy sets and the singletons*

Cycle	Coefficient
High	0.3
Medium	0.6
Low	1



(a) (b)

Fig. 7. Membership functions of cycle time (a). Output surface (b).

4.1. Simple task

Until and unless single-layer cloth-cutting becomes practical and economical, fabric will continue to be die- or knife-cut from multiple layers. Consequently, the most important task in any form of automated textile fabric handling is the removal of a single ply from a stack of the same. This first example refers to design of a gripper that will perform this operation. Assume that the inputs in the KBS are (see Fig. 8):

Required Task: Separation

Status of Material: Free (free from above and free from the edge).

The first rule set produces eight operating principles namely, electroadhesive, adhesive, pinch, clamp, air jet, pin, vacuum, and freezing. This list is inputted to the second rule list, which represent the design constraints, and contains information about the material and the operating principles. The designer, now, is asked to input more data. Assume that data concerning the material are:

Identity: Cotton;

Thickness: 0.3 mm;

Porosity: 20%;

Surface: Smooth;

Density: High;

Molecular weight: Medium;

Weight: High;

Texture: Knitted;

Status of fibers: Clinged; and

Environment: Dust.

The KBS outputs six feasible solutions with the following operating principles:

1. Pin;
2. Pinch;
3. Vacuum;
4. Freezing;
5. Air Jet; and
6. Adhesive.

Every type of adhesive gripper can be used. For every element of this list, the control strategy, the sensing requirements, and the auxiliary equipment are determined. The re-

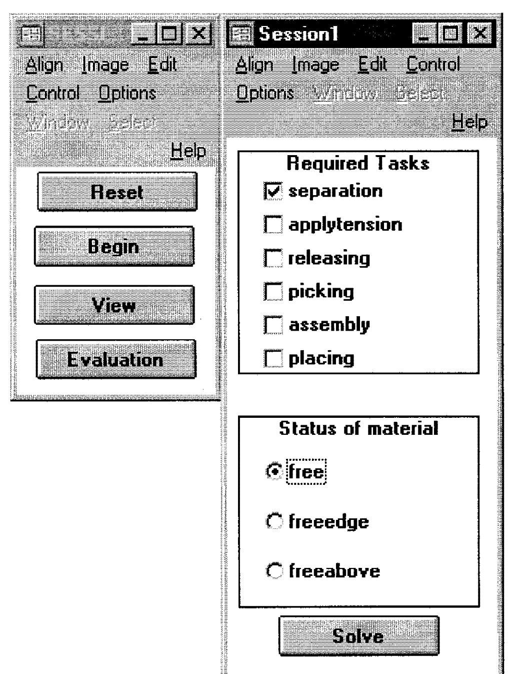
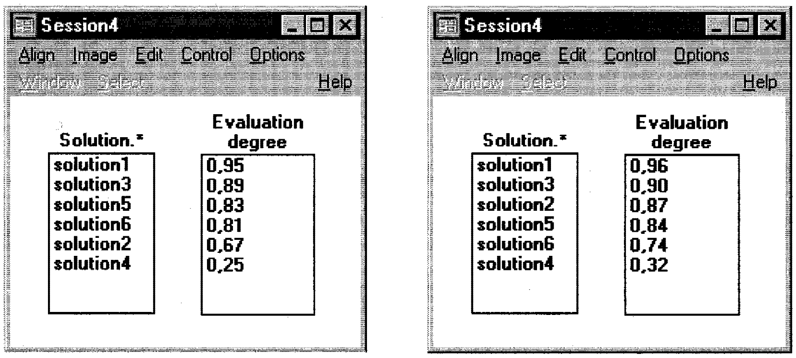


Fig. 8. Initial inputs in the KBS.



(a) (b)

Fig. 9. Evaluation degree of the solutions.

sults can be verified through the works of Kemp et al. (1986) and Parker et al. (1983). An electrostatic gripper could not provide enough force to overcome the gravitational forces of a high-weighted material and knitted texture reduces the holding forces (Monkman et al., 1989). In addition, no way was found to separate a piece of material with thickness approximately 0.3 mm with a clamp gripper (Eiichi et al., 1989). Concerning the control strategy, verification can be made through the work of Gershon (1993).

The best solution can be found by applying combination of the four criteria mentioned in the previous paragraph. The evaluation was used twice for different weights and the results are shown in Figure 9. The weights that correspond to the results of Figure 9a are:

- Maintenance: 0.6;
- Reliability: 0.9;
- Repeatability: 0.7; and
- Cycle time: 0.8.

The weights that correspond to the results of Figure 9b are:

- Maintenance: 1;
- Reliability: 0.3;
- Repeatability: 0.8; and
- Cycle time: 0.7.

The best solution, which is based in the pin operating principle, is shown in Figure 10. The simple structure of the pin

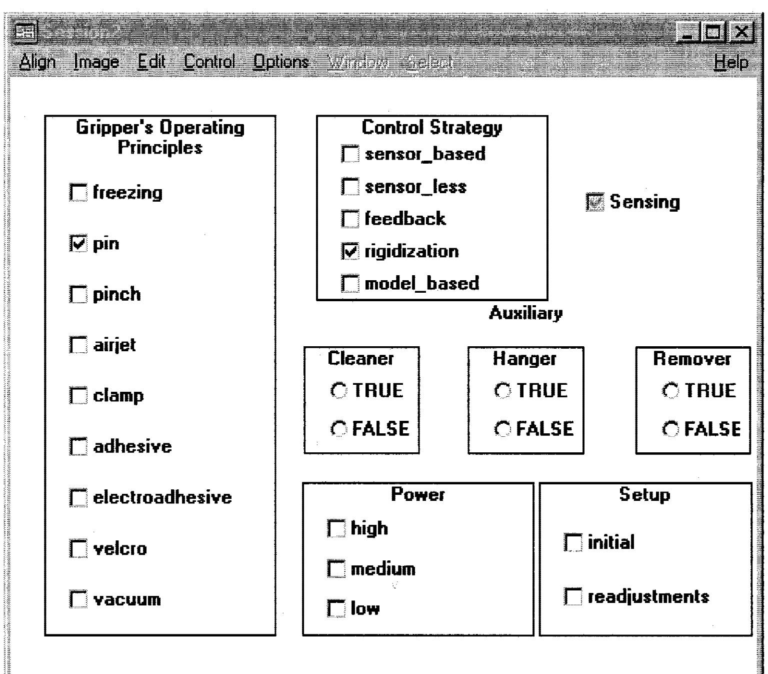


Fig. 10. Final solution of the KBS.

Table 6. *Intermediate results of a complex example*

	Clamp	Vacuum	Adhesive
Apply tension	1	0	0
Assembly	0	1	1

gripper allows use of the simplest control strategy, rigidization, which does not need any sensors. In addition, no auxiliary equipment is needed.

4.2. Complex tasks

Sewing is a complex task and requires a number of tasks to be fulfilled by a gripper. For example, the gripper must stack a single pocket panel on the top of a larger shirt front panel and then, if the sewing operation is not automated, to apply tension to it to be sewed. The second example is the design of a gripper, which will perform all these tasks:

Required Task: Assembly

Apply tension

The first rule set produces one solution for the first task, namely, clamp, and two solutions for the second (vacuum and adhesive).

The designer inputs the following data:

Status of material: Free (free from above and free from the edge).

Identity: Cotton.

Thickness: 0.4 mm.

Porosity: 40%.

Surface: Smooth.

Density: High.

Molecular weight: High.

Weight: High.

Texture: Knitted.

Status of fibers: Free.

Environment: Dust.

The output of the second rule set can be shown in Table 6. The heuristic search method forms one solution by synthesizing gripper operating principles, which is shown in Figure 11. The combination of clamp and vacuum operating principles satisfies both tasks. The adhesive gripper is redundant to this solution. Vacuum and adhesive operating grippers cannot form a final solution because the combined operating principle does not accomplish all the required tasks. (Applying tension cannot be accomplished from vacuum or adhesive grippers.) The control strategy, the sensing requirements, and the auxiliary equipment are shown in Figure 11. The sensor-based, sensor-less, feedback, and model-based control strategies can be applied for the clamp part of the gripper, and the rigidization for the vacuum part. The feedback and sensor-based control strategies need sensors also (Gershon, 1993). The result of this example can be verified by Kolluru et al. (1995). Figure 5 shows that the only operating principle that can apply tension to a fabric is by using

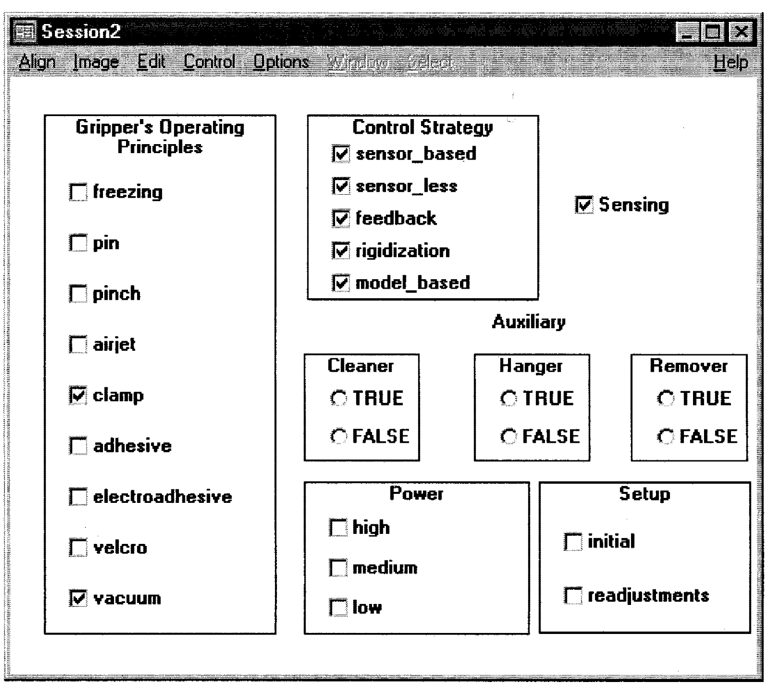


Fig. 11. Final solution of the KBS.

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a clamp grippers. Kolluru et al. (1995) constructed a vacuum gripper for positioning a piece of fabric in the top of another.

In this example, the solution is a multigripper, which as far as it is known, does not exist commercially. So, an original conceptual design was created. No evaluation is needed because the KBS produced only one solution.

5. CONCLUSION

In this paper, a KBS for the conceptual design of grippers for handling fabrics is presented. The designed gripper can handle materials, like paper or polymerics, with their third dimension being small when compared with the other two. The knowledge used was collected by a relatively large number of papers. This knowledge, in terms of gripper, material, and handling process was classified using different approaches and filtered out because there are conflicting opinions in the current literature.

Through the KBS, it is the first time that conceptual design of grippers for handling fabrics is implemented. The existing KBS can achieve only selection of the operating principle of the gripper or choose a gripper from a list of commercially available grippers, but they cannot conclude about the control strategy, the sensing requirements, and the auxiliary equipment of the gripper. The present KBS contributes toward this direction and, additionally, it contributes to the conceptual phase of design because it generates new ideas by applying a combination of existing ones. The heuristic search method can be used in multiple hypotheses problems, when the solution can be a combination of feasible conclusions. It produces the best solution according to four criteria. The KBS developed can be used as an assistance tool in environments where no experts exist or as an advisor when expert engineers have to make critical decisions concerning gripper design.

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APPENDIX A

To find the complexity of the method, consider m tasks that are accomplished partially by n grippers concepts. For every task, a depth first algorithm is executed to specify the grippers' concepts that accomplish the specific task. Each depth-first algorithm needs $O(\max(n_1, n_2))$ time, where n_1 = number of the vertex of the graph and n_2 = number of the edges. In this case the total time is $O(2m)$. For the sorting process, the quicksort algorithm is used with known complexity $O(n \cdot \log n)$ (Aho et al., 1974). In the last part of the algorithm, two processes take place: union and rejection (if needed). In the worst case, all n solutions will be unified. The process of union needs $O\left(\frac{n \cdot (n-1)}{2}\right)$ time. If the first $m - n - 1$ feasible solutions are redundant, then $O\left(\frac{(n-m-1) \cdot (n-m)}{2}\right)$ time is needed for the rejections.

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