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Manipulating deformable linear objects - Contact state transitions and transition conditions -

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Abstract

This paper deals with the robust manipulation of deformable linear objects such as hoses or wires. We propose manipulation based on the qualitative contact state between the deformable workpiece and a rigid environment. First, we give an enumeration of possible contact states and discuss the main characteristics of each state. Second, we investigate the transitions which are possible between the contact states and derive criteria and conditions for each of them. Finally, we apply the concept of contact states and state transitions to the description of a typical assembly task.

1 Introduction

Let us think of two simple tasks which typically occur when assembling industrial goods: Threading a hose through a cutout in a sheet metal housing or fixing an electric wire in a guiding groove. When considering the automated performance of such tasks, we have to face the question of handing non-rigid workpieces robustly and reliably with a robot system. In addition, the expenditure for programming the robot should be as low as possible. In this paper we concentrate on deformable linear objects (DLOs), such as ropes, hoses, electric wires or leaf springs, which can be found in virtually all industrial products.

Compared to the assembly of rigid workpieces, some additional restrictions must be taken into consideration. The shape of the workpiece to be assembled is typically neither exactly known nor constant for the assembly process. While the initial shape depends on the history of the workpiece, the deformation in the assembly process depends on contact forces and gravity. In addition, non-rigid workpieces have an inherent compliance which can hardly be influenced. Altogether, these effectscause high uncertainties which have to be dealt with.

There are two principle ways to cope with these problems. On the one hand, the behavior of the workpiece may be taken into account by means of a quantitative deformation model for computing the shape of the workpiece. On the other hand, the deformation can be regarded as uncertainty which must be compensated while performing the assembly.

The usage of deformation models for handing DLOs has been investigated by several researchers. Zheng et al. determine the required gripper trajectory for inserting a flexible beam into a rigid hole by computing the deflection curve of the beam [10]. Wakamatsu et al. present a general algorithm for computing the shape of elastic DLOs [9]. Those methods can be used if all relevant parameters, geometries and boundary conditions are exactly known. Without additional sensor information, they are likely to fail in the presence of uncertainties.

Other works are based on sensor integration. Inoue and Inaba use a stereo vision system for picking-up a rope and guiding it through a ring [2], while others insert bending beams into holes under friction (Kraus and McCarragher [3], Nakagaki et al. [6]). All of those approaches are used for solving clearly specified tasks, but it is not clear how they may be re-used in other, similar situations.

As far as rigid workpieces are concerned, a lot of works address the problem of developing robust and flexible routines for typical assembling or disassembling tasks. The basic idea is to set up a library of encapsulated, sensor-based routines which can be used as a construction kit for efficiently solving complex assembly problems. Morrow and Khosla demonstrate the efficiencyof this method for inserting different kinds of plug-in connectors [5].

Morris shows that performing assembly tasks can be regarded as stepwise increasing the number of constraints (reducing the degrees of freedom) of one of the mating parts by establishing contact with the other part [4]. Therefore, detecting and manipulating the contact state of the mating parts is a key problem for developing manipulation routines. Any routine changing the contact state of the mating parts (like establishing point contact, transferring point contact to face contact, etc.) forms a module of the construction kit for assembly operations.[1]

Transferring this concept to the handling of DLOs leads to the following questions we con-

[1] Those modules are called 'manipulation skills' in some works. However, the usage of this term is not uniform.

sider in this paper: What are the possible contact states of a DLO in a rigid environment and what are the characteristics of these states (Section 2)? What transitions are possible between these contact states (Section 3)? How can a change of contact state be initiated and what are the preconditions for the change (Section 4)? How can the consideration of contact states be used in assembly tasks (Section 5)? What are the conclusions and how should the work be continued (Section 6)?

2 Contact states

In the following, the contact of a DLO (called workpiece) in a static environment (called obstacle) is regarded. We base our consideration on the following assumptions:

First, the material of the workpiece is isotrop and homogeneous. The workpiece is assumed to be *uniformly curved*, that is, it is either uniformly convex or concave. The deformation caused by gravity and contact forces is elastic, that is, the deformation removes if the stress is released.[2] Example workpieces are a (short) hose or a piece of spring steal. The linear workpiece is gripped at one end and the robot gripper may perform arbitrary linear motions.

Second, all obstacles consist of convex polyhedrons. The friction between workpiece and obstacle is negligibly low. We begin our consideration with a single contact between workpiece and obstacle.

Based on the geometric primitives of DLO and obstacle, Henrich et al. [1] introduce a set of contact states, enumerating all possible contact situations with a single contact. Our analysis is founded on this enumeration. For polyhedral objects, the geometric primitives are vertices (V), edges (E), and faces (F). The linear workpiece has two vertices and one edge between the two vertices. (However, one of the workpiece vertices can be ignored because of the gripper). The geometric primitives are defined by their number of dimensions which is 0 for vertices, 1 for edges and 2 for faces.

The resulting enumeration is shown in Figure 1. We name the contact states by the contact primitive of the workpiece followed by the contact primitive of the obstacle. By combining all possible primitives of the workpiece with all possible primitives of the obstacle, six different contact states are found. An additional state (not shown in Figure 1) is N which indicates that workpiece and obstacle are not in contact.

Like the object primitives forming the contact, the type of contact can by characterized by its dimension which is 0 for *point contacts* and 1 for *line contacts*. The states E/E and E/F may either form a point contact or a line contact. In these

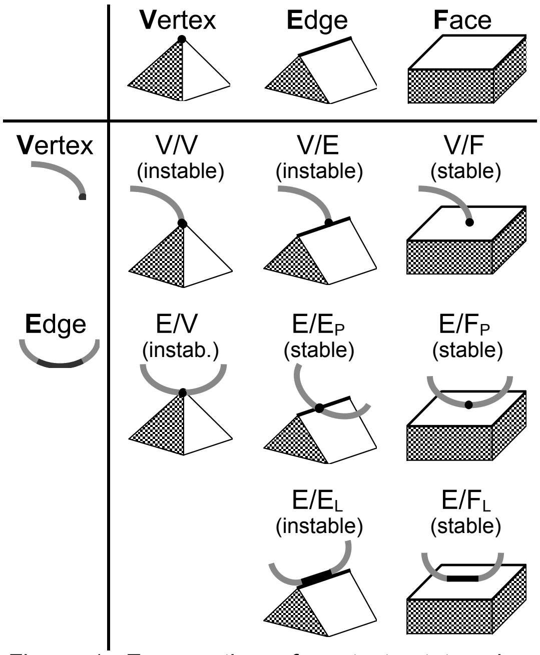

Figure 1: Enumeration of contact states between a deformable, linear object and a convex polyhedron

cases, the contact type is indicated by a subscript P or L, respectively.

An important attribute of each contact state is its stability. A contact state which is kept up if the robot gripper performs a (small) motion in any direction is called *stable*. (However, the contact point or contact line may move). If this condition is not fulfilled, we call the contact state *instable*. Consequently, a stable contact state is especially kept up if the robot gripper is not moved. The stability of each state is also given in Figure 1.

3 State transitions

After defining the possible contact states between workpiece and obstacle, it must be considered which transitions between the contact states may occur and what conditions they depend on. *State transitions* are changes from one contact state to another one without passing intermediate states. For now, establishing a second contact without loosening the first one, i.e., establishing a double contact, shall not be regarded. We distinguish between two types of transitions. A transition which is caused by a distinct action (motion of the robot gripper) is an *initiated transition*. These transitions always start in stable contact states while the following state may be stable or instable. Transitions starting in an instable state and resulting in a new stable state are called *spontaneous transition*. These transitions cannot be directly controlled. They depend as well on the geometric properties of workpiece and obstacle as on the stable state preceding the instable one.

When thinking about transitions between the different contact states, it is helpful to consider which of the states introduced in Section 2 are likely to occur and which are not. On the one

[2] These workpieces belong to the object classes {E–, E+} introduced by Henrich et al. [1].

hand, it is obvious that all of the stable contact states may easily be established. On the other hand, the instable states V/V and E/E_L are unlikely to occur. A transition into state V/V requires a gripper motion guiding the workpiece vertex exactly to the obstacle vertex. A transition to E/E_L requires a gripper motion with the workpiece edge being exactly parallel to the obstacle edge. Any deviation will result in a different contact state. For this reason, the states V/V and E/E_L are not further considered and E/E means E/E_P in the following

The states E/V and V/E are unlikely to occur as *initial contact states*, i.e., following state N. If occurring as initial contact, they will be immediately changed into a stable state. However, both states may occur as intermediate states, e.g., in the sequence V/F → V/E → E/E.

Based on these considerations, a state transition graph can be drawn up which is shown in Figure 2. This graph gives all possible transitions between the contact states (including state N) and is found by means of basic manipulation experiments. The contact states represent nodes while the state transitions represent edges.

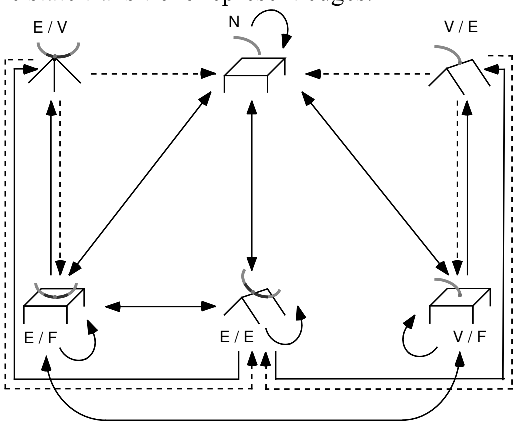

Figure 2: State transition graph. Initiated transitions are shown as solid edges, while spontaneous transitions are shown as dashed edges.

Solid edges starting and ending at the same node indicate stable contact states, i.e., these states may be their own successors. This is the case if a motion of the robot gripper is not large enough to cause a state transition, as described in Section 2.

As stated above, any stable state may be directly established from state N. Therefore, all stable states are connected with state N by solid edges. Transitions E/F ↔ E/E and E/F ↔ V/F are also possible, while there is no link between E/E and V/F. This is caused by the fact that each transition can only change the geometric primitive of either the workpiece or the obstacle, but not both. Please note that in Figure 2 the states E/F_P and E/F_L do not need to be distinguish in most cases.[3] In fact, it is often hard to decide if the workpiece actually is in the state E/F_L or if there is a multiple point contact.

All of the transitions discussed so far are reversible by just performing the same gripper motion in the reverse direction. For transitions beginning in instable states, things are different. It is found that they are only partly reversible. The dashed edges in the transition graph starting from these contact states indicate that there are several possible stable successors for each of them. While transitions leading to a stable state different from N (e.g. V/F → V/E → V/F) are reversible, those transitions leading to N are irreversible.[4]

This behavior becomes clear if the instable states are thought of as borderline cases of the stable ones. Being in a stable state, the workpiece is deformed by a force caused by the contact with the obstacle. A transition 'Stable → Instable → No contact' means that this force is suddenly changed to zero. This leads to an immediate stress-relieve of the workpiece and, thus, an immediate change of the workpiece shape.[5] Therefore, a reverse transition by just performing the same gripper motion in the opposite direction is not possible. The occurrence of irreversible transitions is specific for deformable workpieces. In the handling of rigid objects, transitions are generally reversible. As a consequence, determining the contact situation by means of probing motions, e.g., in Spreng [8], is not applicable for deformable workpieces.

4 Transition conditions

The transition graph introduced in the last section gives no information on the conditions for the occurrence of state transitions. However, such knowledge is necessary for both initiating state transitions in the manipulation process and for avoiding unintended transitions. The analysis of the transition conditions given in this section is only based on some basic characteristic features of the workpiece but not on a numerical computation of the workpiece shape.

4.1 Initial state transitions

We start our considerations with the transitions N → V/F, N → E/E, and N → E/F, i.e., the establishment of an initial contact. It is found that the situation is different for convex and concave workpieces.[6] Figure 3 shows the possible situations if the shape of the workpiece is convex. Possible transitions are N → V/F and N → E/E. Being d_v the length of the trajectory of the workpiece vertex V to the obstacle face F (given by the

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[3] A counter-example is the gluing of the workpiece, e.g., into a groove where a large contact surface is required.

[4] This holds true under the assumption that the workpiece is remarkably deformed in any state different from N.

[5] Those sudden shape changes are typically accompanied by oscillations of the workpiece.

[6] Convexity and concavity are defined with respect to an observer looking on top of face F.

velocity vector $\boldsymbol{v}$[7]) and being P the workpiece point whose trajectory (of length d_P) points towards the obstacle edge, the contact is established as follows: For $d_V < d_P$, the transition is N → V/F, for $d_P < d_V$ the transition is N → E/E. (As in the following, we generally assume that a contact is established at all, i.e., the workpiece does not fail to touch the obstacle).

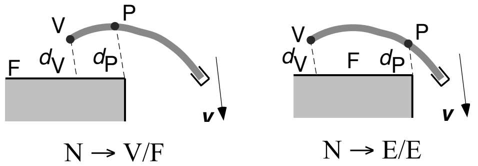

Figure 3: Possible situations and state transitions for establishing contact if the workpiece is convex

If the workpiece is concave, all stable contact states are possible as initial contact. Figure 4 shows the possible situations:

At first, the tangent vector $\boldsymbol{t}_V$ of the workpiece vertex V has to be regarded. If $\boldsymbol{t}_V$ points downwards and the trajectory of V intersects F, the transition is N → V/F. If $\boldsymbol{t}_V$ points downwards but the trajectory of V does not intersect F, the transition is N → E/E (top row of Figure 4). If $\boldsymbol{t}_V$ points upwards (i.e., V is not the workpiece point which is closest to F) the tangent vector $\boldsymbol{t}_P$ of P is decisive. Let us assume that $\boldsymbol{t}_V$ points towards the obstacle (which is here assumed to be semi-infinite) as shown in the middle row of Figure 4. If $\boldsymbol{t}_P$ points downwards, the workpiece point which is closest to F is between P and V. Therefore, the initial contact is E/F. If $\boldsymbol{t}_P$ points upwards, P is the workpiece point closest to the polyhedron. In this case, E/E is the initial contact. If $\boldsymbol{t}_V$ points away from the obstacle, the situation is just inverse (bottom row of Figure 4).

4.2 Stable state transitions

For transitions between the stable contact states V/F, E/E and E/F, the angle α between the tangent vector $\boldsymbol{t}_V$ in the contact point and the obstacle faces is decisive. Let us assume the workpiece being in state V/F, as shown in Figure 5. A transition to E/F occurs if α becomes zero. Depending on the gripper motion, this transition may or may not be connected with a motion of the workpiece vertex V. The same holds true for the transition E/E → E/F.

Provided that the workpiece deformation is elastic (see Section 2), all transitions discussed so far are reversible by just performing the same gripper motion into the opposite direction.

4.3 Spontaneous state transitions

The last kind of transitions to be considered are the spontaneous transitions starting in an instable contact state.

[7] Please note that the velocity vector is constant for all points of the workpiece in state N as long as the gripper motion is linear.

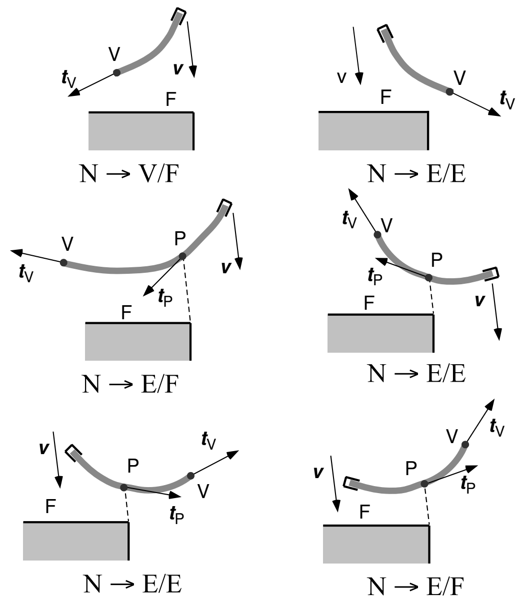

Figure 4: Possible situations and state transitions for establishing contact if the workpiece is concave

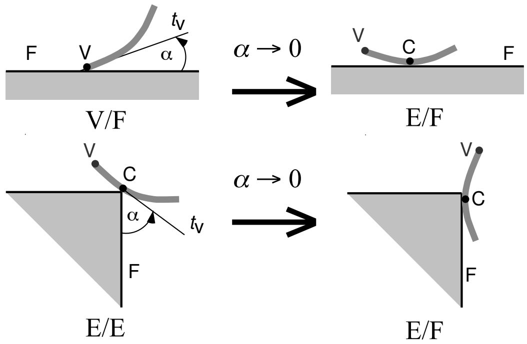

Figure 5: Transitions between stable contact states

First, let us think of the workpiece being in state V/F and being dragged with its vertex over an obstacle edge, i.e., let us think about the spontaneous transition following an initiated transition V/F → V/E.[8] This is the most fundamental case and shall therefore be regarded in some detail. If the faces adjacent to the obstacle edge enclose an obtuse angle, four different situations are possible which are shown in Figure 6, left. Initially, the workpiece vertex is in contact with the left obstacle face F_1 (having tangent plane $\boldsymbol{t}_1$ and normal vector $\boldsymbol{n}_1$). The contact point C moves towards the obstacle edge. The hatched areas indicate the possible workpiece tangents $\boldsymbol{t}_V$ in a contact point C.

1. If $\boldsymbol{t}_V$ is left of tangent $\boldsymbol{t}_2$ of the right face F_2, the resulting stable contact state is E/E. This can be found by simple geometric considerations.
2. If $\boldsymbol{t}_V$ is between $\boldsymbol{t}_2$ and $\boldsymbol{n}_1$, the workpiece vertex gets in contact with face F_2 after passing the

[8] Like in the following, we assume that the gripper motion is not changed when the transition occurs. The resulting contact state given here holds true immediately after the change. If the motion it further continued, contact is generally lost.

edge and the resulting stable state is V/F again.[9] Please note that the contact face has changed from F_1 to F_2, though the final contact state is the same as in the beginning.

3. If $\boldsymbol{t}_v$ is between the normals $\boldsymbol{n}_1$ and $\boldsymbol{n}_2$ of the adjacent faces, contact is lost when the object vertex passes the obstacle edge. This effect is caused by the following: When in contact with face F_1, there exists a contact force $\boldsymbol{F}$ between F_1 and the workpiece vertex. Assuming that friction is negligible (see Section 2), $\boldsymbol{F}$ is normal to F_1. The contact force $\boldsymbol{F}$ can be divided into a portion $\boldsymbol{F}_n$ being normal to the workpiece and a portion $\boldsymbol{F}_t$ being in line with the workpiece. In the quasi-static case (which shall be assumed here), only the normal force $\boldsymbol{F}_n$ causes bending of the workpiece according to its bending rigidity. If the contact point C passes the edge and changes from the first to the second face, the direction of $\boldsymbol{F}$ changes abruptly from $\boldsymbol{n}_1$ to $\boldsymbol{n}_2$. For $\boldsymbol{t}_v$ being between $\boldsymbol{n}_1$ and $\boldsymbol{n}_2$, face F_2 cannot exert a force normal to the workpiece. Thus, contact is lost. (See also Figure 7, below).
4. The case of $\boldsymbol{t}_v$ being between $\boldsymbol{n}_2$ and $\boldsymbol{t}_1$ is similar to Case 2, and results the same way in a stable V/F contact with F_2.

If the angle γ enclosed by the adjacent faces becomes smaller, the angle between $\boldsymbol{t}_2$ and $\boldsymbol{n}_1$, or $\boldsymbol{n}_2$ and $\boldsymbol{t}_1$, respectively, becomes smaller, too. Therefore, the regions discussed as Case 2 and Case 4 are reduced. If γ is acute (<90°), these areas do not exist and only the Cases 1 and Case 3 remain (Figure 6, right).

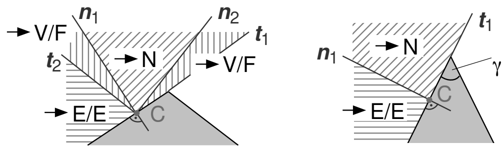

Figure 6: Possible spontaneous transitions following an initiated transition V/F → V/E for obtuse (left) and acute (right) obstacle angle g. The hatched areas indicate the workpiece tangent in contact point C

Second, let us think of the workpiece edge being dragged over an obstacle edge, i.e., an initiated transition E/E → V/E. This problem is just inverse to Case 1 discussed above. According to Figure 6, the resulting stable contact state is V/F if γ is obtuse, while it may be V/F or N if γ is acute.

Third, we consider dragging the workpiece edge over an vertex of the obstacle, i.e., an initiated transition E/F → E/V or E/E → E/V, respectively. In these cases, the plane containing the workpiece must be regarded: If this plane is in between of $\boldsymbol{t}_1$ and $\boldsymbol{t}_2$, (horizontally hatched areas in Figure 6), the resulting contact state is N, i.e., contact is lost. Otherwise, the resulting stable state is E/F or E/E, depending on obstacle geometry and gripper trajectory.[10]

The behavior of DLOs in instable contact states has been validated by experimental investigations and numerical simulations for γ ∈ {30°, 80°, 90°, 100°, 130°}. For the experiments, an industrial robot was used to guaranty precise movements. The simulations where performed with a special simulation software [7]. Figure 7 shows a simulation of the Cases 2 and 3 discussed above.

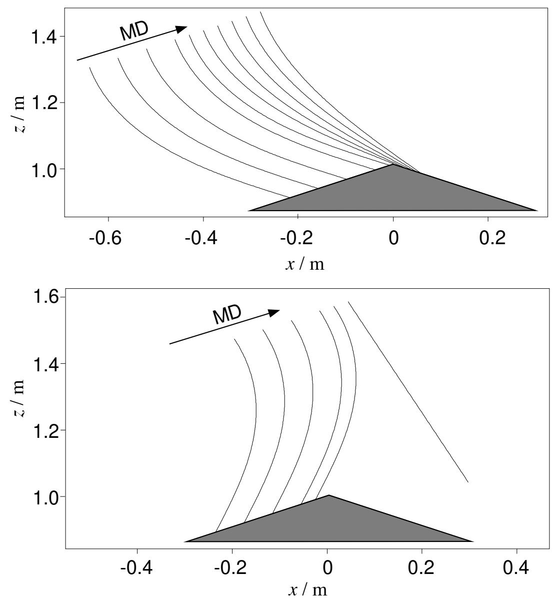

Figure 7: Simulated transition V/F → V/E → V/F (above) and V/F → V/E → N (below) for a copper wire of length 1 m and diameter 1 mm with γ = 130°. MD: Motion direction of the gripper

5 Application to assembly tasks

So far, we have discussed the contact of a deformable linear workpiece with a rigid obstacle from an analytical point of view. This section deals with the application to assembly tasks. When thinking of those tasks, it is found that the assumptions given in Section 2 must be partly relaxed. This affects especially the assumptions of one single contact and of a convex polyhedral obstacle.[11] However, this does neither affect the applicability of the set of contact states nor the rules derived for state transitions.

Let us consider the problem of inserting an elastic pneumatic hose into an U-shaped guiding groove as shown in Figure 8.

Depending on the boundary conditions, there are several possibilities for performing this task. A rather simple and robust procedure is as follows:

[9] In the borderline case $\boldsymbol{t}_v$ parallel to $\boldsymbol{t}_2$, the resulting state is E/F.

[10] This behavior can be derived in the same way as for the Cases 1 through 4 discussed above

[11] The occurrence of a second contact is needed as trigger signal for initiating a new gripper motion. However, the further behavior of the second contacts is not relevant for performing the task.

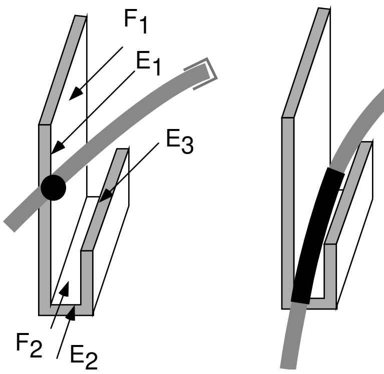

Figure 8: Two states of the insertion process of a hose into an U-shaped guiding groove

1. Establish an initial contact between the edge of the hose and edge E_1 of the groove.
2. Move the hose downwards without loosening contact until the hose touches either of the edges E_2 or E_3.
3. Establish contact between the hose edge and F_1.
4. Move the hose downwards without loosening contact with F_1 until it gets in contact with F_2.

Translating this procedure into a sequence of contact states and state transitions leads to the following:

$$N \rightarrow E/E_1 \rightarrow E/E_1 \wedge (E/E_2 \vee E/E_3)$$
$$\rightarrow E/F_1 \rightarrow E/F_1 \wedge E/F_2$$

Obviously, it would be rather simple to generate a robot program for performing this task if a library of sensor-based, encapsulated routines for the required state transitions was available. Performing assembly tasks in this way requires neither exact knowledge about the mechanical workpiece properties nor a quantitative calculation of the workpiece shape.

6 Conclusions

In the assembly of rigid workpieces, the consideration of contact states and state transitions has proven to be a suited method for creating robust manipulation routines for multiple purposes. We expect that this holds true for deformable workpieces as well. In this paper, we investigate contact states and state transitions of deformable linear objects in a rigid environment. The application to a typical industrial problem shows that this principle can be easily used for describing assembly tasks.

There are especially two further questions which need to be investigated if we want to use contact states and state transitions for robot programming: How can the contact states and state transitions be detected by means of sensor systems and what is necessary to perform the state transitions reliably and robustly with a robot system? The investigation of these questions will be our next step.

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