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Picking-up Deformable Linear Objects with Industrial Robots

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Abstract

This paper deals with the problem of picking-up deformable linear workpieces such as cables or ropes with an industrial robot. First, we give a motivation and problem definition. Based on a brief conceptual discussion of possible approaches we derive an algorithm for picking-up hanging deformable linear objects using two light barriers as sensor system. For this hardware, a skill-based approach is described and the parameters and major influence factors are discussed. In an experimental study, the feasibility and reliability under diverse conditions are investigated. The algorithm is found to be very reliable, if certain boundary conditions are met.

1 INTRODUCTION

When considering automated assembly of industrial goods, picking-up the workpieces always is the first step of the task. For the manual assembling process, the workpieces are typically supplied unsorted in containers, boxes, etc. Though this is the cheapest method, it matches the well-known box-picking problem and is therefore very hard to automate. For rigid workpieces, the problem can be solved, e.g., by using magazines or pallets. For most non-rigid workpieces whose shape is neither constant for all workpieces nor exactly known, the problem is more complex.

In this paper, we discuss the problem of picking-up hanging deformable linear objects (DLOs) with a standard industrial robot. The motivation for investigating the problem is given in the task of automated assembly of cable forms into final products (e.g., washing machines or car doors).[1] However, the solution is found to be applicable to several other kinds of deformable workpieces like hoses or ropes.

The task investigated here is picking up cable forms which are fixed at one point whose position is approximately known. The cable forms are hanging freely in a gallows with their main plug (Figure 4).

Figure 1 shows a section of the driver's door cable forms of the MERCDES Class A and MERCEDES Class C for which the problem is investigated. Because the first step of the assembly process is to thread the main plug through a cut-out in the door. Therefore, it is not possible to grasp the cable form directly at the plug. Instead, it must be grasped about 0.3 m beneath the fixing position. Due to gravity, the cable shape can be approximated by a vertical line. However, the exact shape is unknown.

The task should be solved using a purchasable industrial robot and a common robot programming language. All sensor systems should be robust, cheap, and established in the industry.


Figure 1: Section of the driver's door cable form for MERCDES Class A (left) and Class C (right)

For the problem given above, we derive an algorithm based on the principle of manipulation skills (MS), see e.g. Morrow et al [3].[2] This implicates the following requirements:

- The MS effects a change in state of the workpiece (transfer from state 'hanging freely' to the state 'grasped').
- For the programmer, the MS is independent of both robot hardware and sensor systems.
- The MS is encapsulated and needs as few parameters as possible. Note that the parameters must not concern the sensor systems which are needed for executing the skill.
- The MS is robust concerning the initial state and environmental conditions.
- Errors must be detected and handled.

The problem of picking-up a hanging rope has been investigated by Inoue and Inaba [2]. In that work, a special experimental robot set-up is used which is supported by a stereo vision system for determining the shape of the rope.

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[1] Today, this task is performed completely manually.

[2] For the application of this concept to DLO's, see also Henrich et al. [1], Remde et al. [6].

However, the usage of a vision system generally requires special illumination and background conditions which are hard to meet in industrial environments. Additionally, this approach is rather expensive concerning both sensor hardware and data processing. Therefore, it does not fulfill our requirements given above. Some problems concerning the manipulation of DLOs based on computer vision are considered by other authors, too, e.g. Smith [7], but they do not address the picking-up problem.

Several works propose mathematical deformation models for handling deformable workpieces, e.g. Wakamatsu et al. [8] or Nakagaki et al. [4]. These models mainly consider elastic deformation of homogenous objects. Please note that under these assumptions the task of picking up a linear hanging object could be solved very easily because the object should hang in a straight vertical line. Actually, the shape is highly influenced by the inhomogenous structure, internal stress, and plastic deformation caused while manufacturing, transporting, and storing the cable forms. It is almost impossible to regard these influence factors in a quantitative deformation model. In [4], an initial plastic deformation is considered, but a complex stereo vision system is required for determining the shape.

When considering the task of picking up hanging DLOs the following questions must be addressed: What approaches are generally possible (Section 2)? What kind of algorithm does fulfill the requirements given above and what are the major influence factors (Section 3)? Does the algorithm prove to be reliable in an experimental investigation (Section 4)? What are the conclusions and how should the work be continued (Section 5)?

2 POSSIBLE APPROACHES

The most simple approach for solving the task of picking-up hanging DLOs is the usage of a gripper with large jaw aperture in order to cope with the unknown cable shape. However, this solution is not applicable for two reasons: First, the jaws of (pneumatic driven) purchasable grippers can typically be completely open or completely closed, but can not be controlled to stay in any intermediate state. This might cause problems in the subsequent mounting process where the free space around the gripper is typically small. Second, this method may only be applied if the fixing position of the DLO is rather far from the gripping position, otherwise the stress acting on the cable may become very large and cause damage to the DLO.

As the task of picking-up a DLO can be traced back to the basic problem of determining the shape of a three-dimensional curve in space, any three dimensional vision system (e.g., based on stereo vision [2]) might be employed for determining the gripping position. This solution is straight-forward, but requires high expenditure concerning both sensor system and data processing.

Because the orientation of the hanging DLO can be assumed to be approximately vertical, the position of only one point must be determined for picking-up. Thus, the problem of determining the workpiece shape can be reduced to the problem of determining the 2D coordinates of one DLO point $\boldsymbol{P}_{\text{Grasp}}$ in a plane which is approximately perpendicular to the DLO. In this case, the usage of a light section scanner (or a spot range finder combined with a scan motion of the robot) is straight forward.[3]

However, a further simplification is possible if both coordinates of $\boldsymbol{P}_{\text{Grasp}}$ are determined sequentially, as described in the following section.

3 DESCRIPTION OF APPROACH

3.1 Algorithm

If no background has to be considered (i.e. the distance between the DLO and any surrounding object is larger than the measuring range of the sensor systems), two light barriers B_1 and B_2 are found to be sufficient for determining $\boldsymbol{P}_{\text{Grasp}}$. Barrier B_1 is a reflex barrier which is mounted on top of the gripper, B_2 is a miniature one-way barrier which is integrated into the gripping jaws.

Figure 2 gives a top-view of the process which is performed in three steps: First, the gripper performs a *scan motion* in η-direction with velocity v_S (Step I). This motion is stopped when the DLO is detected by reflex barrier B_1. Then, the position of the gripper is adjusted to align the center axis of the gripper with the optical axis of B_1. Second, the gripper performs a *feed motion* in ξ-direction with velocity v_F until light barrier B_2 is interrupted (Step II). Finally, the gripping jaws are closed in Step III.[4]

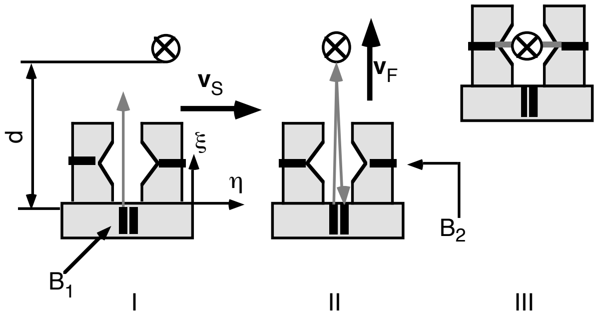

Figure 2: Top-view of the gripping process (B_1 and B_2: light barriers, v_S and v_F: scan and feed velocity, d: distance between scan path and DLO, η and ξ: direction of scan and feed motion)

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[3] Please note that the price for a suited light section scanner is about 30 times higher than for the light barriers employed here.

[4] Alternatively, a 2D camera image may be used for determining the direction of the feed motion. In this case the camera system is used instead of B_1.

This algorithm given above requires the following parameters:

- Start position of scan motion (given implicitly by the gripper position when starting the algorithm).
- Velocity v_S and v_F of scan motion and feed motion, respectively.

A straight-forward implementation of the algorithm shows that it is principally feasible, but the reliability is rather poor. This is caused especially by the following two reasons:

First, the correct grasping position $\boldsymbol{P}_{\mathrm{Grasp}}$ is given by the center of the cross section of the DLO. However, the algorithm described above gives the correct grasping position only if both the diameter of the DLO and the light beam are infinitesimal small (Figure 3 left). This assumption does not hold true for real DLOs and light barriers. The state of a one-way barrier is changed if a certain portion of the light beam is interrupted by the cable. An analogue effect can be observed for reflex barriers. Consequently, both scan motion and feed motion are stopped too early, resulting in a positional error $\Delta\boldsymbol{x}_{Barrier}$ which amount depends on both DLO diameter and light barrier (Figure 3 right).

This positional error can be avoided in the following way: If the change in state of a light barrier occurs, the current gripper position is stored in a variable $\boldsymbol{x}_{\mathrm{Begin}}$ without stopping the motion. When the light barrier has passed the DLO, the state of the barrier changes again. This position is stored as $\boldsymbol{x}_{\mathrm{End}}$ and the motion is stopped. The correct η- or ξ-coordinate of $\boldsymbol{P}_{\mathrm{Grasp}}$ can than be computed as mean value of $\boldsymbol{x}_{\mathrm{Begin}}$ and $\boldsymbol{x}_{\mathrm{End}}$.

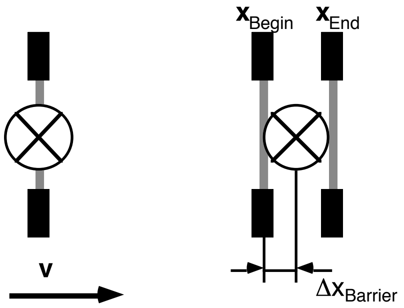


Figure 3: Ideal (left) and real (right) state changes of a light barrier ($\boldsymbol{v}$: gripper motion, $\boldsymbol{x}_{\mathrm{Begin}}$ and $\boldsymbol{x}_{\mathrm{End}}$: positions of state changes, $\Delta\boldsymbol{x}_{\mathrm{Barrier}}$: resulting error)

Second, the algorithm presumes that the optical axis of the reflex barrier is perpendicular to the scan path of the gripper. However, for purchasable reflex barriers, the optical axis is typically not exactly specified. This results in a false gripper trajectory when performing the feed motion. Consequently, the DLO is not exactly in the center of the gripper when the feed motion is stopped (Step III in Figure 2), but shows a deviation Δx_{Axis} in η-direction. Being α the angle between the optical axis and the perpendicular of the scan path, and d the distance between scan path and DLO, the amount of deviation is given by:

$$\Delta x_{\mathrm{Axis}} = d \tan \alpha$$

If Δx_{Axis} becomes larger than the tolerable positional error, the gripper will either touch the DLO with one of the jaws without gripping it or completely miss the cable.

The deviation may be taken into consideration by either exactly adjusting the reflex barrier on top of the gripper or by simultaneously rotating the gripper by α with respect to the normal of the $\xi\eta$-plane before starting the feed motion. In the experiments described below, this second method is employed. In both cases, α must first be determined experimentally.

Thus, the algorithm may be described in the following form.

```
procedure Pick_Skill($v_S$, $v_F$);
const $\Delta_{Gripper}$;   {Cartesian offset between $B_1$ and gripper}
      $\eta$, $\xi$;        {Cartesian direction of scan and feed motion}
      $B_1$, $B_2$;         {Interrupt ports for light barriers)
var x:POSE ;               {Cartesian position}
begin
    Open_Gripper();
    x := Eval_Barrier($\eta$, $v_S$, $B_1$);
    x := x + $\Delta_{Gripper}$;
    Move(x);
    x := Eval_Barrier($\xi$, $v_F$, $B_2$);
    Move(x);
    Close_Gripper();
end;

function Eval_Barrier($\psi$: DIRECTION,v: REAL, B: PORT):POSE;
var $x_{Begin}$, $x_{End}$: POSITION;  {Cartesian interrupt positions}
begin
    Start_Motion($\psi$, v);
    while signal(B) = FALSE do;
    $x_{Begin}$ := Current_Position();
    while signal(B) = TRUE do;
    $x_{End}$ := Current_Position();
    Stop_Motion();
    Eval_Barrier := ($x_{Begin}$ + $x_{End}$)/2;
end;
```

3.2 Error Handling

The implementation as manipulation skill requires robustness concerning both environmental uncertainties and false parameters. When performing the picking-up operation, the following kinds of errors may occur which must be recognized and possibly handled:

- If there is no object within the measuring range of B_1, the scan motion is performed without any change of state of B_1. In this case, the scan motion should be stopped automatically after scanning a given maximal distance. With $d_{\max}$ being the measuring range of B_1, the scan motion may be repeated after moving the gripper about $d_{\max}$ in ξ-direction.

- To avoid damage, it should be certified that any object which the robot tries to pick up is small enough to be grasped by the gripper. This is possible by defining a maximal motion distance $\Delta s_{\max}$ between the state changes of each barrier, with $\Delta s_{\max}$ being smaller than the jaw aperture a. If the second state change does not occur while moving this distance, the detected object is too large and the process must be stopped.
- In some cases, the DLO can be detected successfully but can still not be grasped. This occurs if the velocity of the feed motion is too high. In this case, the cable touches the gripper body (and thus starts oscillating!) before the feed motion is stopped. This error can be detected by using the one-way barrier. For succeeding in picking up the DLO, the one-way must be interrupted after closing the jaws. If this is not fulfilled, the complete process may be repeated with reduced feeding velocity.

Generally, the algorithm requires that the DLO to be picked up does not move. This requirement can be met in most cases. However, it is found that oscillations of the DLO do not disturb the process as long as their amplitude is low.

3.3 Timing

Any change of state is processed by the light barriers within a response time $\Delta t_{\text{Barrier}}$ which is typical for each barrier. The state of change is transferred to the robot controller via interrupt port which is processed with an uncertainty $\Delta t_{\text{Interrupt}}$. So the total time uncertainty is given by

$$\Delta t = \Delta t_{\text{Barrier}} + \Delta t_{\text{Interrupt}}$$

Being v the (constant) motion speed of the gripper, the distance uncertainty is thus given by:

$$\Delta x = v\,\Delta t,$$

where Δx always points into the direction of the gripper motion.

Please note that an object may not be detected at all if the time between the two state changes of a barrier is too short (i.e., the velocity is too high). This may be caused either by the light barrier which does not give the interrupt signal or by the robot controller which ignores very short pulses on the interrupt lines.

3.4 Further Influence Factors

Besides the parameters discussed above, some additional factors have to be considered:

Because the state change of a reflex barrier is triggered by an intensity change of the reflected light, it is obvious that both the responsiveness and the response time of a reflex barrier depend significantly on the optical properties of the reflecting object. For achieving high responsiveness, the intensity change should be as high as possible. Therefore, a plain white surface of the DLO is suited best. Note that this does not hold true for the one-way barrier where the light beam is interrupted by the DLO. In this case, the responsiveness is independent of the optical properties of the workpiece surface, as long as it is opaque.

Besides the optical properties of the DLO, the measuring distance of the reflex barrier has a major influence on responsiveness and response time. The best values are achieved if the object is in the middle of the measuring range while they are considerably worse especially at the distant range limit.

4 EXPERIMENTS

4.1 Experimental Setup

For investigating the feasibility and reliability of the algorithm described above, the following experimental setup is used:

The robot system is a KUKA KR 15 industrial robot with 6 DOF and 15 kg payload which is controlled by a PC-based robot controller KR C1.

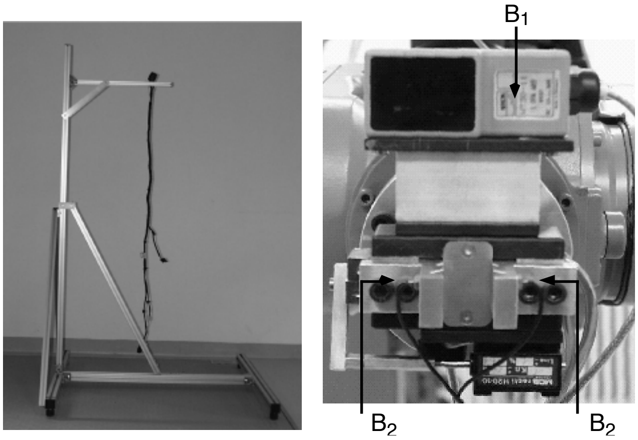


Figure 4: Experimental setup: Cable form hanging in a gallows (left) and gripper with reflex barrier B_1 and one-way barrier B_2 (right)

The robot program is written in the C-like KUKA Robot Language (KRL). For connecting the light barriers, two interrupt inputs are used which can be read by KRL. The robot is equipped with a standard pneumatic parallel jaws gripper with prismatic jaws and jaw aperture $a = 20$ mm. It is controlled by two proportional valves [5].

The cable form is hanging freely in a gallows which is set up using a purchasable construction kit (Figure 4, left). The position and orientation of the gallows are approximately known.

Light barrier B_1 is an infrared reflex barrier SICK WT 30-11 with a measuring range of (15..100) mm. The response time $\Delta t_{\text{Barrier}}$ is specified with 15 ms. This barrier is mounted on top of the gripper. Barrier B_2 is a miniature infrared one-way barrier which is integrated into the gripping jaws (Figure 4, right).

As test objects, the cable forms for the driver's door of the MERCEDES Class C and Class A shown in Figure 1 are used.

4.2 Experimental Results

In an experimental study, the influence of the following factors on the reliability is investigated:

- scan velocity v_S,
- scan distance d between barrier B_1 and cable form, and
- type of cable form.

The experiments are performed under the following conditions:

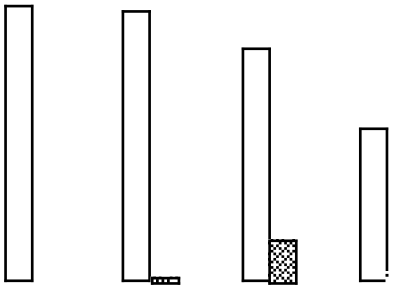
- scan distance $d = 0.08$ m (if not specified otherwise),
- feed velocity $v_F = 0.1$ m/s (the feed velocity always has to be quite low to prevent the cable touching the gripper body. At this speed, detecting the cable is not critical),
- 100 single trials per experiment.

In every trial, we distinguish three possible results:

- successful (s): the cable form could be picked up and is positioned correctly in the prism of the gripping jaws,
- false (f): the cable form could be picked up, but is not positioned correctly, and
- unsuccessful (u): the trial failed and the cable form could not be picked up at all.

For each experiment, the number H of successful, false and unsuccessful trials is given.

The influence of the scan velocity v_S on the reliability for cable form A is shown in Figure 5. The result verifies the assumption that the reliability decreases if the velocity of the scan motion is increased. The false trials are caused by an edge of the gripping jaws touching the cable before grasping it. For very high scan velocities ($v_S = 0.8$ m/s) the cable form sometimes could not be gripped at all due to delayed interrupt signals in some cases.



Please note that the uncertainty of the interrupt detection of the KR C1 controller is specified with $\Delta t_{\text{Interupt}} = 14$ ms. With $\Delta t_{\text{Barrier}} = 15$ ms for the reflex barrier, the total uncertainty is $\Delta t = 29$ ms. This results in a positional uncertainty $\Delta x = 5.8$ mm for the lowest velocity $v_S = 0.2$ m/s. Regarding the gripper aperture $a = 20$ mm and the diameter $D_A = 13$ mm of the cable form, this uncertainty is hardly tolerable. However, the reliability is 100% in this case. For a scan velocity $v_S = 0.4$ m/s, the positional uncertainty is $\Delta x = 11.6$ mm which is far too much. However, the reliability is still 98%, because the uncertainty only gives a worst case estimation. The real positional error is much smaller in most of the trials.

Figure 6 shows the influence of the optical properties of the DLO surface. While cable form A is taped with a black textile tape, cable form C consists of multiple single cables with PVC sheathings of different colors. Obviously, the reliability is much higher for cable form C than for cable form A if the scan velocity is high. Note that for cable form C no trial is completely unsuccessful even for $v_S = 0.8$ m/s. For this velocity, the nominal total positional uncertainty is $\Delta x = 23.2$ mm! In an additional series, the black surface of cable form A is taped with a plain white PVC tape (A w). In this case, a reliability of 99% is obtained. This experiment shows the high dependence of $\Delta t_{\text{Barrier}}$ on the optical properties of the workpiece.

In principle, cable form C might not be detected at all by either of the barriers if the clearance between the single cables is considerable. However, this could not be observed in the experiments. It is supposed, that this effect occurs if laser instead of infrared light barriers are used, since the focal point is considerably smaller for laser barriers.

The influence of the scan distance d on the reliability for cable form C with a scan velocity $v_S = 0.6$ m/s is shown in Figure 7. For $d = 0.08$ m, the reliability is 100%. (Note that this could obtained for cable form A only with a scan velocity $v_S = 0.2$ m/s, see Figure 5!). At a scan distance $d = 0.1$ m (which is the specified limit of the measuring range of the reflex barrier), the cable form could not be detected in 9% of the trials.

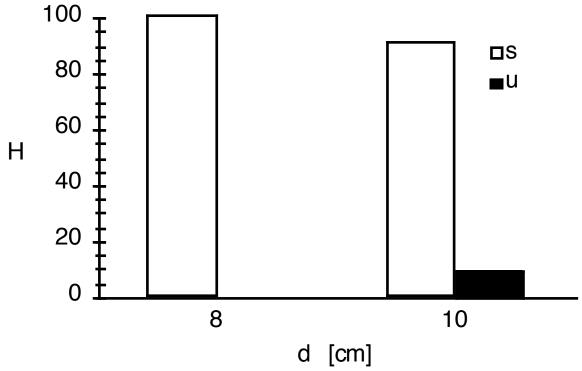


Figure 7: Influence of the scan distance *d* on the reliability

5 CONCLUSIONS

The investigation shows that the problem of picking up hanging DLOs can be solved by a simple algorithm and low-cost sensor systems if certain boundary conditions can be met. The scan distance *d*, the scan velocity v_S and the color and surface of the DLO are identified to be the major influence parameters and investigated in an experimental study. Generally, increasing the scan velocity effects a decrease in reliability. A reliability of 100% can be achieved if the scan velocity is moderate. The threshold value for achieving a reliability of 100% can be significantly increased if the cable has a light plain surface. For achieving best results, the scan distance should be in the middle of the measuring range of the reflex barrier.

The time required for performing the complete process (scanning, feeding and grasping) is supposed to be completely sufficient for typical industrial applications. However, it may be further optimized for special applications, e.g., by carefully choosing the object color and using a (laser) reflex barrier with a short response time.

Using two light barriers proves to be a good solution for the picking-up problem if no background must be considered. However, if the DLO is lying on an irregular shaped surface or any obstacles within the measuring range have to be considered, a more general approach is needed. In these cases, a light-section laser scanner gives all information required without having the complexity of a stereo vision system. This approach is currently being investigated.

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