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On the Design of a Twist-Lock Manipulator

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Abstract: The paper describes the problem of automatic (dis-) mounting of twist-locks at maritime containers. This task is complicated due to various container sizes and various twist-lock types. A manipulator mechanism in a twist-lock station is the preferred solution. The end-effector needs a universal device for rotation of the cone of the twist-lock and a gripper. A special gripper mechanism, having preloaded springs, has been investigated with respect to its compliant behaviour. This concerns both the elastic and the hysteresis effects, due to slip between jaws and twist-lock. Both effects can be used advantageously to protect the manipulator against overload and to allow misalignment of the twist-lock.

Keywords: Automatic mounting, Parallel jaws gripper, Preloaded spring, Compliance, Hysteresis

1 Introduction

For a background to the problem see figure 1, the transshipment of containers for seagoing vessels. Containers on deck have to be secured with twist-locks, connecting the corner castings between two containers placed upon each other. Usually these twist-locks are manually inserted in or removed from the bottom corner castings, while the container is still suspended by the cables of the quay crane. The twist-locks belong to the ship and simple storage bins are used at the quayside for the twist-locks coming from the ship. The paper deals with a proposal to (dis-) mount the twist-locks automatically using a separate twist-lock station (TLS). The method aims to save costs, reduce the transshipment time and eliminate health risk for the terminal personnel [2, 3].

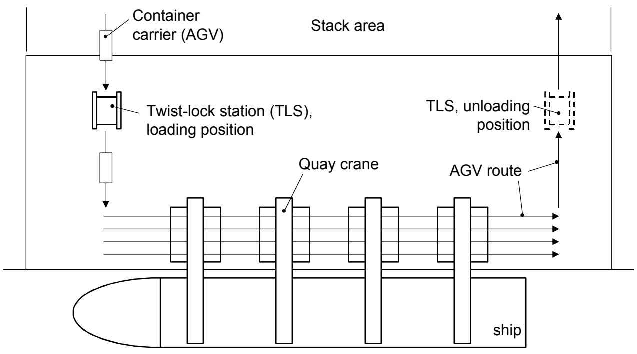

Figure 1 Terminal layout

Twist-locks of the so-called semi-automatic type will be considered, see figure 2. They have a housing, a shaft with two cones and an additional device (handle or chord) for manual (pre)setting the shaft into either a locked or an unlocked position. The cones match with the standard holes in the corner fittings. Their shape is such that penetrating the hole causes rotation of the shaft. The automation concept makes use of this property: the shaft will be rotated by the cones and not by the additional devices for manual rotation, the latter being highly non-standard. The problem focuses on the mechanism to (dis-) mount a twist-lock to one corner casting. The container is assumed to be transported on the quay by a flatcar (AGV), leaving each corner free for the twist-lock.

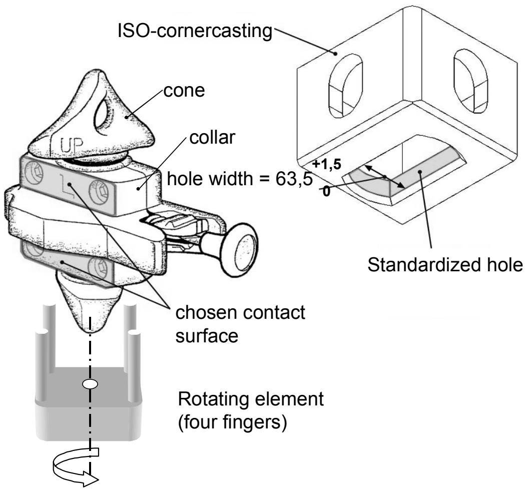

Figure 2 Semi-automatic twist-lock

2 Manipulator Requirements

The twist-lock station will be equipped with four identical manipulator mechanisms, one at each corner, which will work simultaneously. Because containers can have various standard lengths (like 20, 40 and 45 ft), the manipulators need to be guided along the station (x-direction), see figure 3. A perpendicular motion in y-direction (or φ) is required to both sides of the guiding rail, to reach both the mounting position and the storage position. The end-effector needs no rotation in the xy-plane, so a parallel four-bar mechanism suits very well. By controlling the degrees of freedom (DOF's) in x- and y-direction, the stopping inaccuracy (usually 5 cm) of the container is not critical. The end-effector needs a third DOF (lift) in z-direction. In the method a storage tray has been proposed, at which the twist-locks will be placed upside down. The 180° rotation (yz-plane) is the fourth DOF. It is advantageous to consider the end-effector frame as an extension. It enlarges the working area of the manipulator to both sides of the guiding rail.

The end-effector itself comprises a gripper and a cone rotating element. The latter can simply be a plate with four fingers, wide enough for all cone shapes (figure 2). Such an element can be moved to any rotation angle by digital control.

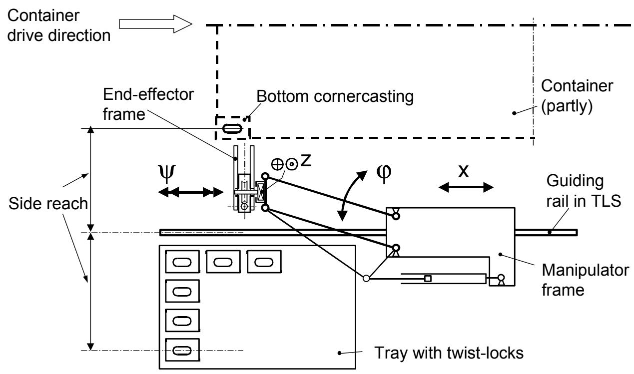

Figure 3 Manipulator concept

The gripper acts on the collar near the lower cone. It must be designed such that the cone rotation will not be hindered. It further needs a rather high grasping force (a twist-lock has a mass of about 8 kg) and an extra wide opening to avoid collision with the lower cone (in any angular position). The situation appears from figure 4.

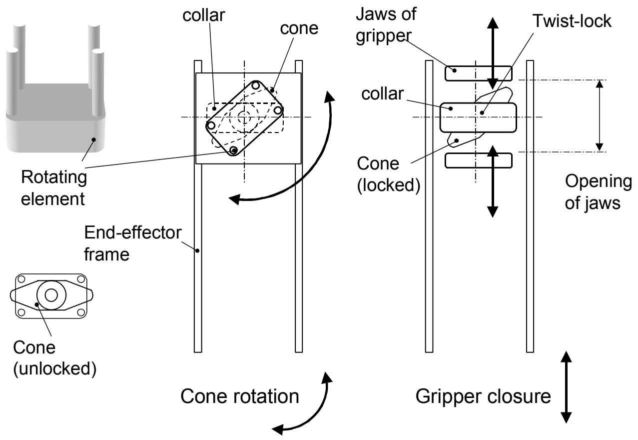

Figure 4 The end-effector

3 Gripper Configuration

Any gripper configuration with parallel moving jaws can be applied, like the one depicted in figure 5a (found in [1]). It was observed however that several points concerning the functionality of the gripper need attention.

A high grasping force tends to a wide diameter of the driving cylinder and a wide jaw opening tends to a long cylinder stroke. A big cylinder volume can be avoided, since the high force is only required at the end of the stroke. A nonlinear force transmission, by a link mechanism, can be advantageous.

The collar width has no well-defined tolerance (only the tolerance of the hole is specified in the ISO-standard). Collar widths found in practice range from 57 – 62 mm. To guarantee sufficient grasping force two solutions are frequently used. Firstly (preloaded) springs can be added, this always allows the piston to move to the same closing position. Secondly the pressure in the cylinder can be measured. In the latter case the end-position of the piston is undefined.

The first method has a certain advantage: misalignment of the object to grasp is allowed within the compliance of the springs (figure 5b). For our purpose this is obviously important, since the container, to which the twist-lock is connected, has a very large mass (about 30 tons). Small vibrations of the vehicle suspension system could easily damage the gripper or the manipulator. There is also a disadvantage: the twist-lock and the springs form an oscillation system, usually having a bad dynamic positioning accuracy.

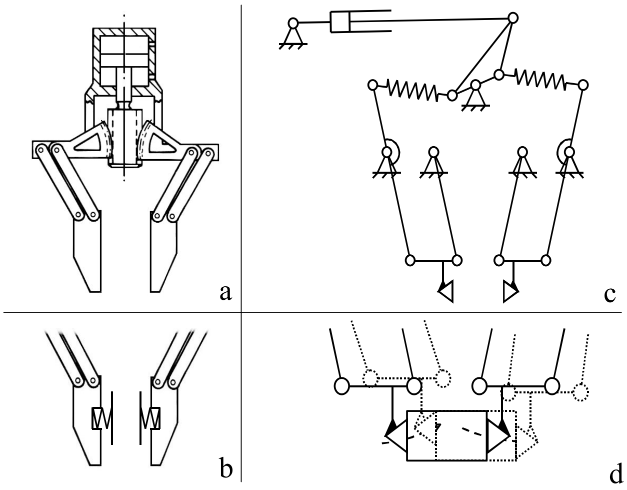

Figure 5 Parallel gripper configurations

The springs need not be situated at the jaws itself, but can be a part of any link, as drawn in figure 5c. It has been noticed however that the latter configuration introduces a special compliance effect: a vertical motion will occur relatively between the jaws, generating a friction force that could be applied to absorb the energy of compliant motion (friction hysteresis, figure 5d). This effect has been investigated with respect to its usefulness to improve compliant behaviour of the gripper [4].

4 Investigation of Compliant Behaviour

For this investigation two assumptions were made:

Firstly the driving cylinder is in the position where the gripper is closed. In this case the triangular lever can be considered as "fixed". The mechanism model used for the investigation is like drawn in figure 6, having the horizontal motion of the twist-lock as input.

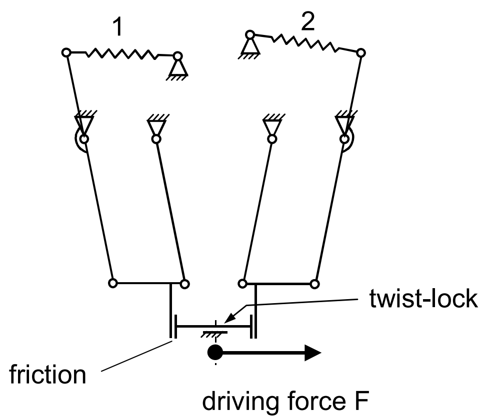

Figure 6 Mechanism model

Secondly a tilting effect of the twist-lock will be neglected. Actually this tilting depends on the collar dimensions (mainly the ratio of width and height). Usually the twist-lock will be held in orientation either by the container or by the storage tray surface.

A quasi-static force analysis will be performed, using a standard computer program for numerical analysis of kinematics and dynamics [5]. Mass forces have been left out consideration.

4.1 Spring characteristic

Assuming a linear compression spring with constant stiffness, the preloaded application has a spring characteristic of the connecting rods (indicated 1 and 2 in figure 6) as drawn in figure 7. The minimum application length (at maximum pressure force) can be passed physically, but overload may damage the spring. The maximum application length (at minimum pressure force) cannot be passed physically. Instead the corresponding jaw will loose contact with the object to hold. To simulate this, the (theoretical) spring characteristic can be modeled as in figure 7. Loose of contact will thus be considered as vanishing of the normal force in the connecting rod, while the rod exceeds its maximum lengths.

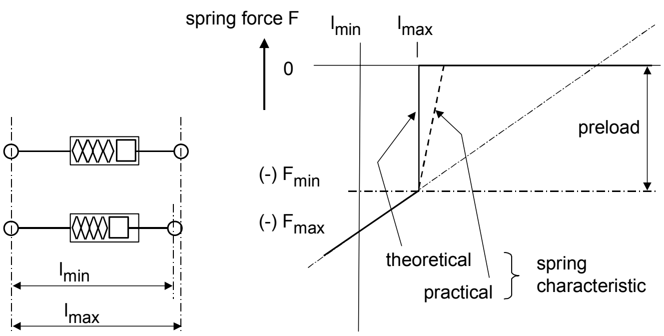

Figure 7 Characteristic of preloaded spring

The computer program offers a spring model consisting of a linear spring acting at a certain working range, and different stiffness outside this working range. This model has been used for the investigation task. Only one adaptation had to be made: a jump (infinite stiffness of the theoretical spring) is not allowed. For practical use a very high stiffness has been substituted, but the application intends to operate mainly outside the “working range” of this spring.

Two identical springs have been chosen for the two connecting rods. The characteristic is such that the contact force in closed position (static, at the jaw) ranges from 800 to 900 N, for a twist-lock collar width between 57 and 62 mm. The maximum length of the connecting rods corresponds to a collar width of 54 mm. With this choice each jaw will be displaced at least 1.5 mm to build up the preload of the spring.

4.2 The friction effect

The software as available does not support friction, so the friction forces have to be added in a post-processing phase. The theory used to implement this is given below.

The twist-lock will be moved, for instance from a leftmost position to a rightmost position, and back. The driving force without friction is called F_0. Performing motion and force analysis, firstly the slip velocity between each jaw and the twist-lock (called $\dot{s}_L$ and $\dot{s}_R$, indices L and R for left and right jaw respectively) and secondly the contact forces (called σ_L and σ_R) will be calculated. Assuming friction coefficients μ_L and μ_R, the internal forces simulating friction are then:

$$\sigma_{wL} = sign(\dot{s}_L) \cdot \mu_L \cdot |\sigma_L| \quad (1)$$

$$\sigma_{wR} = sign(\dot{s}_R) \cdot \mu_R \cdot |\sigma_R| \quad (2)$$

They contribute to the driving force, acting along displacement direction x, in accordance with the balance of virtual work:

$$\Delta F = \sigma_{wL} \frac{ds_L}{dx} + \sigma_{wR} \frac{ds_R}{dx} \quad (3)$$

in which the derivatives are just kinematic transfer functions that can be obtained from the analysis run.

The friction not only influences the driving force, but also the internal forces, and among them the contact forces at the jaws. The friction equations like (1) and (2) could be programmed in the software and solved iteratively, but this has not (yet) been carried out. Instead, for this purpose of investigation, the contact forces can be estimated with the result of the previous mechanism position. The horizontal force equilibrium of the twist-lock in position i is satisfied accurate enough by:

$$\sigma_{L(i)} = \sigma_{0L(i)} + \Delta F_{(i-1)} \quad (4)$$

$$\sigma_{R(i)} = \sigma_{0R(i)} - \Delta F_{(i-1)} \quad (5)$$

where σ_0 indicates the contact force without friction. In the first position the correction term ΔF can be set zero. The result in position 1 is less accurate then.

4.3 Calculation results

Several theoretical experiments have been set up with the gripper, holding a twist-lock, to investigate the compliant behaviour. The symmetry axis of the twist-lock will be moved from left to right over a distance of 20 mm (from -10 to +10 mm). According to equations (1) and (2) the driving direction is important, not the driving speed itself. Regarding the chosen spring characteristic this will certainly include situations where one of the jaws looses contact with the twist-lock. Overload of springs will be neglected; it concerns just numerical experiments.

One experiment has been done for the full range of twist-lock widths, from 57 to 62 mm and assuming no friction. The resulting driving force has been depicted in figure 8, showing the compliant behaviour of the gripper. Typically there is a middle part with a certain compliance (stiffness), which is independent of the width, and which should be regarded as the proper working range of the compliance. The stiffness value can be understood with the concept of “two springs in series”. The position where one of the jaws looses contact can be recognized by a jump, because of the preload of the spring that becomes ineffective (in figure 8 it concerns the steep part due to the spring characteristic). The range where only one jaw is in contact has typically a lower stiffness then the middle part. This can be explained with the rule that the total stiffness of two springs in series has the combined stiffness of the single springs:

$$c_{tot} = c_1 + c_2 \qquad (6)$$

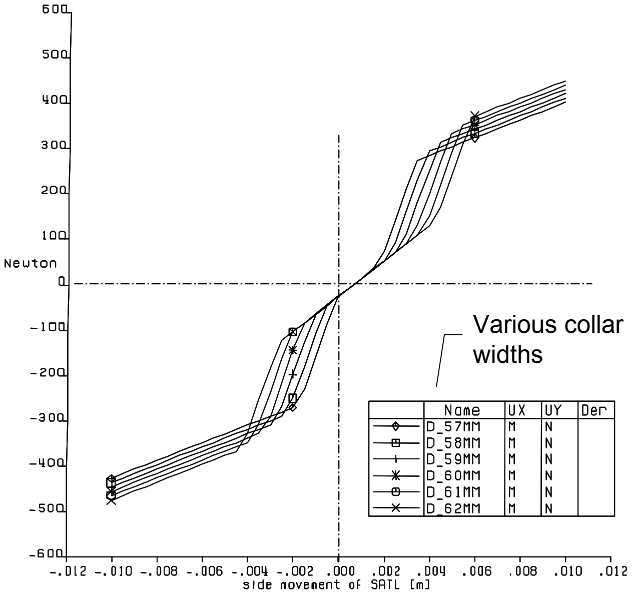

Figure 8 Compliance characteristic without friction

It is noticed that the compliance characteristic is not precisely symmetrical. This is due to the fact that the kinematic loops of the left and right jaw are indeed not precisely symmetrical. In the paper this aspect will not be discussed further.

In a second experiment the friction coefficient f has been varied for a certain width of the twist-lock (f = 0.0…0.6). The result can be viewed in figure 9. The compliance characteristic of the first experiment can be recognized, but now there is also the hysteresis effect. It can be detected for instance that, for a friction coefficient f=0.6, a side force at the twist-lock which is less then 80 N, will not cause slip. This is a design critical value, because it is now possible to hold the twist-lock horizontal and still no slip in the jaws will occur (The horizontal orientation will be passed when the twist-lock is rotated upside down).

5 Experimental Verification

The twist-lock manipulator has partly been built (without the x- and y- motion) and tested in a laboratory environment [4]. The main objective was to test the proper working of the end-effector, which contains both the gripper and the rotation unit. The tests were successful: several types of twist-locks have been inserted and removed to and from corner castings of containers and tray storage holes. A second objective of the laboratory equipment is to measure, under manual control, the precise angular positions of the cone rotation tool for (un-) locking. These rotation angles are required in the control software.

To test the compliance capability the following experiment has been done. The corner casting has intentionally been given a misalignment and it was tried to (dis-) mount the twist-lock. It appeared that a misalignment of 4 mm, and for some twist-lock types even 9 mm, still leads to a correct result. This cannot be explained with possible clearance between twist-lock and corner casting. It is obvious that the compliance of the gripper, as designed and built, works fine.

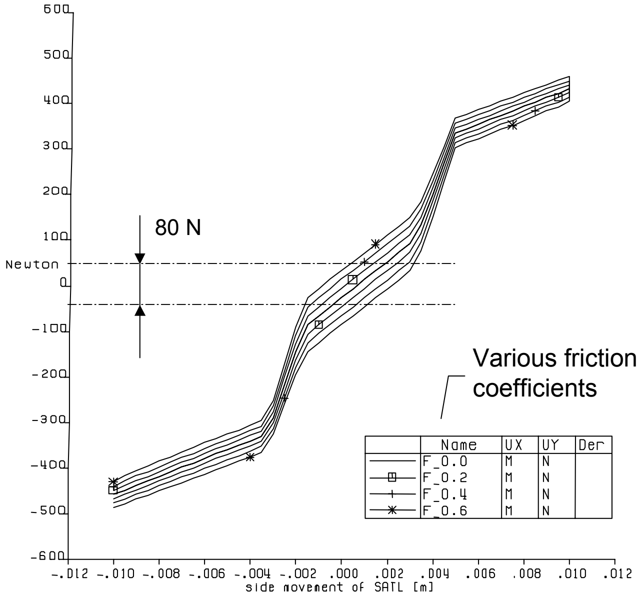

Figure 9 Compliance characteristic with friction (twist-lock width 60 mm)

6 Conclusion

A couple of preloaded springs applied in a gripper mechanism introduces compliant behaviour with characteristics, like

- a range with linear spring resistance against misalignment,
- extra high spring resistance outside this range (loss of preload),
- extra resistance due to friction hysteresis.

These effects can be influenced with the spring characteristic, the friction coefficient between jaws and object to grasp, and the slip behaviour (kinematic transfer functions of relative motion) of the gripper mechanism.

Based on these effects a dedicated gripper mechanism for manipulating twist-locks has been designed, which can deal with some misalignment and overload. These properties are mainly useful when a manipulator needs to grasp or connect to an object with a big mass, that is in an inaccurate position or may be in oscillation.

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