Modelling and application of the self-locking phenomenon in the context of a non-discrete impact clutch

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This paper describes an application of the self locking phenomenon in order to realize a non-discrete impact clutch. It is used to generate velocity jumps in an underactuated robot manipulator. Due to control reasons the impacts have to be made possible at arbitrary times, which calls for a non-discrete device. Different design alternatives are listed and a numerical simulation as well as a possible mechanical design of the self-locking mechanism are presented.

1 Introduction

Passively actuated robot manipulators are characterized by the capability of changing the number of degrees of freedom of the dynamical system. This structure variance can either be achieved by applying a friction force (e.g. by using a classical braking device) or impulsive impact forces. A typical way of imposing impacts on dynamical systems are bed stops or jaw couplings, which however according to geometrical reasons enable impacts at predefined and discrete positions only. Since the robot manipulator of this work will serve as an experimental platform for control strategies of underactuated non-smooth mechanical systems, impacts have to be possible at arbitrary times and positions. Only if this is possible, the precalculated velocity profile including velocity jumps can be maintained without any additional control effort (see left graph in Fig.1). The manipulator itself has the shape of a double pendulum with two rotational joints connecting the inertias of the arms.

2 Non-discrete impact clutches

Whenever planar rigid bodies are contacting each other, the impact of each contact point can happen in two directions. This can be either in normal direction or in tangential direction, depending on the geometric nature of the closing of the contact.

2.1 Design alternatives

The impact in normal direction can be realized by a mechanism shown in Figure 1(a). The basic element is an advancing block depicted in the shape of a fork which moves at a distance \( \Delta \phi \) from the arm. In order to induce an impact at \( t = t_{imp} \), the block has to be decelerated or being stopped completely within a time span \( \Delta t \) before the impact (see Fig.1(b)).

If the impact occurs in tangential direction, it is caused by friction. By choosing the appropriate geometry it is achieved that the degree of freedom remains blocked, or more precisely the contact being involved in the joint remains closed, even though the load is increased. A typical mechanism using this method is the freewheel (Fig.1(c)), which however only works in one direction.

Fig. 1 Motivation for a non-discrete clutch, Design alternatives

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By evaluation of the different solutions regarding control effort and easy manufacturing an edge design has been chosen. It uses the self-locking phenomenon for generating a total inelastic impact. The geometry of the contact is such that the normal force instantaneously increases to a very large value. By applying Coulomb’s friction law the friction force rapidly raises as well, resulting in a friction impact.

### 2.2 Contact kinematics and kinetics

In order to calculate the dynamics of the system containing both contact partners (clamping edge and rotating disc) the contact kinematics of the unilateral constraint between both bodies (see [2] for a complete description) have to be examined. By solving the nonlinear equation given in (1) the shortest distance \(|r_{C_1C_2}|\) between the two nearest points \(C_1\) and \(C_2\) of bodies 1 and 2 can be found, in order to detect a closing of the contact, where \(t_i\) and \(n_i\) denote the corresponding unit vectors in tangential and normal direction on the surface of body \(i\). The vectors \(s\) and \(q\) contain the parameters along the contour and the generalized coordinates of the mechanical system.

\[
f(s, q, t) = \left( \frac{r_{C_1C_2}^T t_i}{n_i^T t_2} \right) = 0 \tag{1}
\]

Together with the tangential and normal contact velocities \(\dot{g}_T = \gamma_T = t_1^T v_{C_1} + t_2^T v_{C_2}\) and \(\dot{g}_N = \gamma_N = n_1^T v_{C_1} + n_2^T v_{C_2}\), using the velocities \(v_{C}\) of the contact points taken as momentary rigid body points, the kinetic equations can be stated (see [3] for a short overview of this procedure). For the purpose of having a unique contact configuration, an edge profile causing only one contact point has been chosen (Fig.2(a)). The limit cases of choosing a suitable contour are given by pure rolling (no self-locking or braking action) and mere braking (edge profile is identically to the disc profile).

### 2.3 Numerical Simulation and Mechanical Design

A time-stepping algorithm according to [1] is used for a numerical simulation (10000 steps for 0.5s) of the mechanism. At \(t = 0.2\)s the edge \((m_1 = 0.1kg, R_1 = 0.03m)\) is accelerated by a torque of 0.01Nm towards the disc \((R_2 = 0.02m, \text{inertia corresponding to a mass of } 15kg \text{ at a radius of } 0.3m)\). The initial gap between edge and disc is 0.5mm, the angular velocity of the disc \(\dot{\beta} = \pi/s\). Independently of the chosen stepwidth self-locking occurs after 0.2ms resulting in an abrupt stopping of the disc (the impact coefficient in normal direction is \(\epsilon = 0\), the coefficient of friction \(\mu = 0.3\)). The mechanism fulfils its purpose, the cost however is a very high normal contact force which both bodies have to withstand (Fig.2(a)).

Since the functionality of the self-locking mechanism has to be bidirectional, the edge design has been carried out two-sided. As shown in Fig.2(b) several edges are symmetrically placed around the rotating disc, which avoids a special bearing for the shaft to handle radial displacements. The bearings of the edges consist of brass collars and are placed within two steel rings, carrying the radial load during the self-locking action. The disc on the shaft is made of hardened steel and fixed via a fit-in key. The actuation of the edges is simultaneously being carried out by a disc with rods in axial direction, reaching into the single edge bodies. Loosening of the edges after locking is achieved by the rebound of the attached arm of the manipulator.

### References

