ISSN 1992-6502 (Print)
Vol. 17, no. 6 (59), pp. 28-32, 2013.
Vestnik UGATU
ISSN 2225-2789 (Online)
http://journal.ugatu.ac.ru

UDC 004.7

A SOFT-CATCHING STRATEGY FOR TRANSPORT BY THROWING AND CATCHING

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Submitted 2013, June 9

Abstract. Automatized transport by throwing and catching offers a number of advantages over traditional transportation techniques, especially in terms of reconfiguration time and flexibility in general. State of the art approaches dealing with this topic focus on catching of the object without consideration of the impact forces on the object. Here a strategy for minimizing the forces during catching and the related simulation results are presented.

Keywords: material handling; projectile; transport-by-throwing; robotic catching.

1. INTRODUCTION

Experiments with robotic catching have been conducted for over 20 years now [1] as a benchmark for robotics and robotic throwing and catching has also been proposed as a flexible approach to material handling [2].

The main composition of such a transportation system is illustrated in Fig. 1.

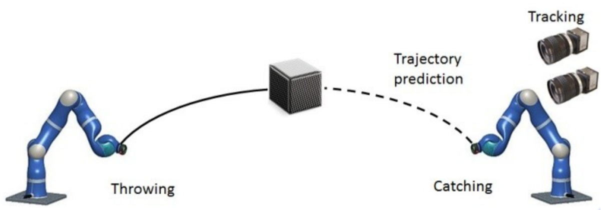

Fig. 1. Basic composition of a transport-by-throwing system

The four parts of such a system are the throwing and the catching device, a system for trajectory and interception point prediction and a tracking system used to acquire the input data for the prediction system. The requirement for the trajectory prediction and tracking system arises from the fact that catching of a thrown object is only possible if the interception position is known prior to the time when the object reaches the position. The catching device has to be positioned accurately at the position before the object reaches it in order to achieve a successful catch.

Different approaches to predict the trajectory have been proposed [1, 3–5] which are mainly based on physical models of the flight. Results achieved are in the range of 70 % successful catching rate [1, 3, 4, 6].

A main attribute to the approaches is that the objects are caught with a static positioning of the catching device. While different strategies for catching are examined in one report [3] the reduction of the impact-force of the object when being caught has not been targeted so far.

2. PROPOSED SYSTEM AND CATCHING STRATEGY

The catching strategy is described in an elaborative way where the architecture and prerequisites are outlined first, the basic idea is presented which lead to the specific position and finally the strategy to maximize catching velocity is given.

Architecture

Based on the KUKA LBR 4+ robotic arm (mounted on a wall, compare Fig. 2) and the provided fast research interface a bio-inspired catching system, covering all parts outlined in Figure 1 is being developed currently.

The strategy for soft catching is topic here while other aspects like the throwing system, tracking system and trajectory prediction are left out of scope.

Using a remote host interfacing with the robot's controller via the FRI the usage of the Reflexx Motion Library is enabled. Based on this library online trajectory generation is possible [7], even the prospective planning of a robot's motion is possible. This prospective trajectory planning is used to achieve a partly synchronization of the catching device's velocity with the thrown object. For the sake of simplicity a known relation between position of the object and time is assumed.

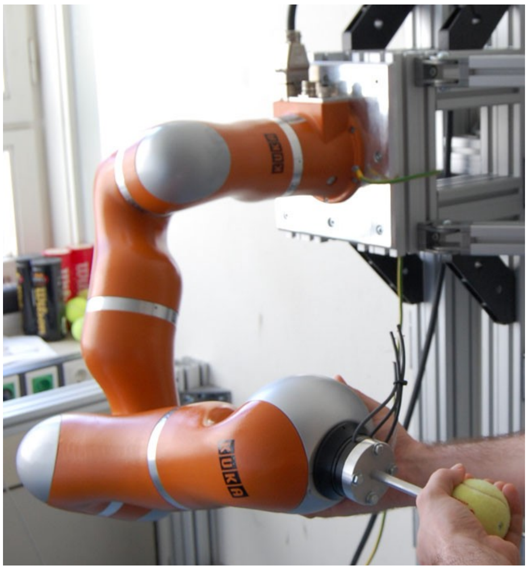

Fig. 2. KUKA LBR 4+ mounted to a wall; joints J1 to J7 from base to end effector

Prerequisites

The robot used for catching and thus the base for the calculation is a KUKA LBR 4+ with a maximum joint velocities of 112,5 °/s for all but joint J5 180 °/s. The maximum torques for the joints J1–J7 are: 200, 200, 100, 100, 100, 30 and 30 Nm. In addition a catching device is mounted on the flange where the center is the tool center point (TCP). The catching device (CD) has a weight of 0,5 kg and a length of 0,16 m from flange to TCP. From now on all joints J1-J7 are referred as J1, J2, J3, J4, J5, J6 and J7.

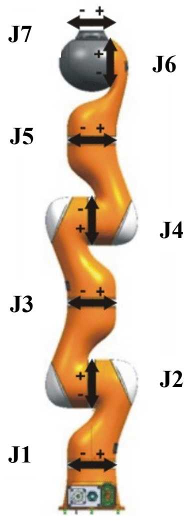

Fig. 3. Joint definitions: J1-J7 from base to flange

The relatively limited maximum velocity of the KUKA LBR 4+ robotic arm requires using the individual joints in a way to maximize the effective velocity of the end effector/catching device. The whole strategy to explain the catching movement will be discussed in three steps, where each step adds complexity:

Basic Idea

Due to the longest length of the lever the robot's base-joint (J1 compare Fig. 3) has the most significant influence on the achieved catching velocity. For maximal effect the following strategy is used:

Based on the predicted trajectory the optimal interception point for maximum velocity of the catching device is determined. The position where the object's trajectory is normal to the line between the robot's base-joint's pivot and the interception point candidate is defined as interception position. With other words: in case the robot only had one joint allowing rotation and bending (J1, J2) and an adjustable length of the link, the circular trajectory of the end effector could be aligned in one point where the tangents of the end effector's trajectory and the thrown object's trajectory align – this is the position where the prior mentioned condition is true.

Fig. 3 illustrates the relations between the base-joint and the trajectory for a discrete calculated trajectory (100 Hz sample rate).

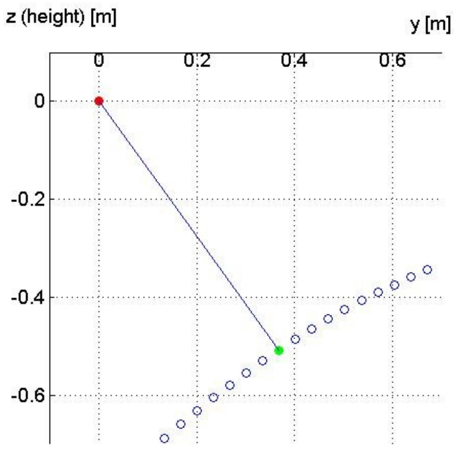

Fig 3. Illustration of the interception position's determination (simulated data)

The figure shows an illustration of the predicted trajectory and the planned interception position. In terms of Fig. 2 the viewing position is opposing the wall the robot is mounted to, the thrown object is arriving from the right side. The red dot illustrates the robot's joint J1 pivot while the green dot represents the interception position. The connection between the red dot and the green dot is an abstraction of the robot's arm and the angle between this line and the trajectory is 90°.

Specific Position

After determining the interception point the next step is to calculate the positions of the robot's joints to reach the interception position. The following method is used:

The position of J1 is determined based on the angle between the *z*-axis and the robot-arm (compare Fig. 3). The links between J2/J4, J4/J6 and the TCP of the catching device are aligned in one line (compare Fig. 3 with Fig. 4)

Based on the distance between the axis of J1 and the interception position the required position of J4 can be calculated (in interception position all links of the robot-arm are in one plane, the upper-arm and lower-arm/hand are part of a triangle where J4 defines the angle between them both). J4 defines the distance between the robot's J2 and the interception point.

From the position of J4 the position of J2 can be derived.

The position of J3 has to be fixed at 0 ° in order to keep the links of the arm in one plane. The usage of the other joints (J5, J6 and J7) will be discussed shortly. An illustration of the catching position with J5 = J6 = J7 = 0 ° is given in Fig. 4.

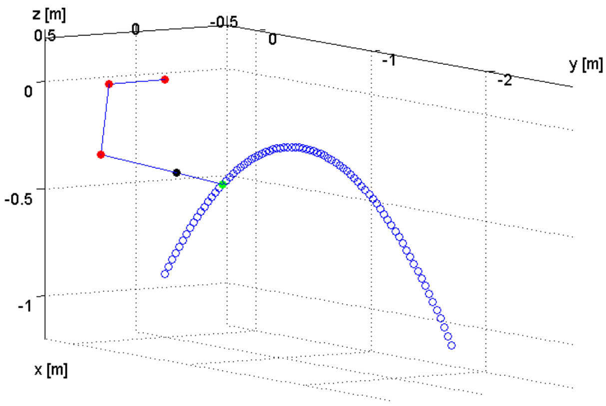

Fig. 4. Illustration of the interception position's

Maximizing Catching Velocity

As mentioned before maximizing the velocity of the catching device is a main goal to minimize the impact forces on the thrown object during catching. At the time the thrown object reaches the interception position the catching device has to be positioned there as well (according to the prior described strategy). In addition to this interception position another position (waiting position) can be calculated from which the robot is able to reach the interception position within a given time limit. This movement is used to accelerate the catching device mounted to the robot. All seven joints of the robot can be used for this acceleration movement but their impact on the final velocity varies. Initially a common angular acceleration for each joint is considered which results in the same angular difference between the interception position and the waiting position.

J7 has a lever length of 0 mm cannot be used for velocity increase but it is used to align the catching device with the trajectory.

Joints with their axis normal to the plane of the robot's links in the interception position have no influence on the velocity reached and thus are kept constant (J2 and J4).

J6 can be used to increase the velocity of the catching device if J5 is not in zero position. To maximize the effect of J6, the tangent of the movement caused by J6 has to align with the trajectory of the thrown object in the interception point. This is accomplished by J5.

In addition to the J6 also J3 and J1 are used to generate velocity. This is similar to a human softly catching an object with shoulder internal rotation (J1), humeroradial joint (J3) and the wrist movement (J6) in action.

Estimated Catching Velocity

The achieved velocity of the catching device depends on the velocity of the joints J1, J3 and J6 at the instant of interception and the catching position of the whole robot. The restricting factors for the joint-velocity are the maximum joint velocities, the maximum joint torque (limiting maximum acceleration) and the available time for acceleration. While the first two factors are limitations caused by the robot (hardware specification) the latter depends a lot on the precision of the trajectory prediction over time. The earlier a high accuracy prediction is available the higher the achievable velocity. Still the maximum velocity limit of the robot's joints remains.

Based on the overall mass of the robot and the maximum torque of each joint the maximum necessary time for accelerating to the maximum velocity is estimated. The moment of inertia is estimated based on the total mass of the robot (16 kg) that is assumed to be equally distributed over the 7 links. This assumption is considered pessimistic as the mass of the last spherical link is obviously smaller compared to the others. All other links are assumed to be cylindrical (d = 0,24 m; again pessimistic assumption).

The following scheme is used: cyl-l denotes a cylinder rotating along its axis, cyl-d denotes a cylinder rotating at the end of the cylinder and sph denotes a sphere rotating along an axis through the centre point.

Table 1

J1	Mass [kg]	Dimension [m]	Distance [m]	*J* [kgm²]
cyl-r	2,29	0,240	0	0,016
cyl-l	11,43	0,878	0	2,964
cyl-r	0,50	0,160	0,958	0,463

Based on the maximum torque $M_{1,max}$ of 200 Nm a maximum angular acceleration $\alpha_{J1,max}$ of 58,5 1/s² or 3354 °/s² results. The related acceleration time to maximum velocity (112,5 °/s) $t_{accel1,max}$ is 33,5 ms. $M_{3,max}$ 100 Nm; $\alpha_{J3,max}$ = 75,7 1/s² = 4339 °/s²; $t_{accel3,max}$ = 25,9 ms (112,5 °/s), $M_{6,max}$ 30 Nm; $\alpha_{J6,max}$ = 2330 1/s² = 133544 °/s²; $t_{accel6,max}$ = 0,8 ms (112,5 °/s).

Table 2

J6	Mass [kg]	Dimension [m]	Distance [m]	*J* [kgm²]
sph	2,29	0,078	0	0,006
cyl-r	0,50	0,160	0,078	0,007

These estimations have been verified based on a test where the extended arm (with a 500 g tool) is accelerated with J2 from 0 °/s to 110 °/s with an acceleration of 3000 °/s². This test resulted in acceleration within the torque limit of 200 Nm but during the deceleration phase the torque limit was violated. This on one hand can be explained by jerk of the control algorithm during the deceleration phase where the torque limit is violated and on the other hand shows that the used acceleration is close to the limit of the arm.

The maximum estimated acceleration time of the relevant joints (J1, J3, J6) is 33,5 ms. This means that the maximum joint velocity of each of the three joints can be reached if the interception position is known 33,5 ms prior to the instant of interception. Considering the relation to the whole flight phase of 780 ms (simulated tennis ball throw from 2,5 m distance with 5,3 m/s and 42° inclination) only the last 4,3 % of the flight phase have to be used to accelerate the catching device. Catching the thrown object with maximum velocity in each relevant joint is possible based on this estimation.

3. SIMULATION RESULTS

Based on the previously introduced catching strategy and a simulation of a thrown object's trajectory the achieved velocities of the catching device for a number of trajectories are calculated. The difference in impact energy for hard and soft catching is used as a measure for the benefit of soft catching.

The object's throw is calculated based on a simulated throwing device with an average throwing velocity of 5,1 m/s and an 42 ° inclination with normal distributed variances of 2,5 % for velocity, 2,5 % for inclination angle and 5° sideways. The origin of the thrown objects is 1 meter below and 2,5 m away from the robot's root.

In a simulation with 100 throws the mean relative velocity of the object in comparison with the catching device could be reduced from 4,13 m/s to 1,39 m/s. This results in an reduction of the kinetic energy at impact from 0,467 J to 0,027 J or an average reduction to 5,8 % with a range of 3,6–11,7 % (min–max).

Table 3

J3	Mass [kg]	Dimension [m]	Distance [m]	*J* [kgm²]
cyl-r	2,29	0,240	0	0,016
cyl-l	6,86	0,668	0	1,020
cyl-r	0,50	0,160	0,748	0,284

4. CONCLUSION

The proposed strategy for soft catching has shown the potential to reduce the relative kinetic energy to a significant lower level. In simulation the minimum effect has been a reduction to 11,7 % which means to an eighth of the energy when catching the object in an hard manner. This reduction enables the approach of transport by throwing to be used for a higher number of thrown objects that demand soft catching.

The next step is to test the proposed strategy with the robot. This is possible based on the simulated trajectories in order to isolate the aspects of soft catching. If successful the integration with the trajectory prediction and tracking can be done. Based on a mobile acceleration measurement system the benefits of soft catching can thereafter be examined during practical experiments.

Further aspects are the timely synchronization of the image acquisition with the robot's command and measurement data and the bio-inspired prediction system.

ACKNOWLEDGMENTS

The research work of K. V. Mironov is supported by the European Erasmus-Mundus Program.

REFERENCES

1. B. Hove and J. Slotine, “Experiments in robotic catching,” In: *American Control Conference*, 1991, pp. 380–385.
2. H. Frank, N. Wellerdick-Wojtasik, B. Hagebeuker, G. Novak, and S. Mahlknecht, “Throwing objects – A bio-inspired approach for the transportation of parts,” in *IEEE Int. Conf. Robotics and Biomimetics*, ROBIO '06, 2006, pp. 91-96.
3. Won Hong and Jean-Jacques E. Slotine, "Experiments in hand-eye coordination using active vision," *Lecture Notes in Control and Information Sciences*, pp. 130-139, 1995.
4. U. Frese, B. Bauml, S. Haidacher, G. Schreiber, I. Schaefer, M. Hahnle, and G. Hirzinger, “O-the-Shelf Vision for a Robotic Ball Catcher,” in *IEEE Int. Conf. Intelligent Robots and Systems*, USA, 2001, pp. 1623-1629.
5. D. Barteit, H. Frank, and F. Kupzog, “Accurate prediction of interception positions for catching thrown objects in production systems,” in *Industrial Informatics*, INDIN 2008. 6th IEEE Int. Conf., 2008.
6. B. Bäuml, T. Wimbock, and G. Hirzinger, “Kinematically optimal catching flying ball with a hand-arm-system,” in *Intelligent Robots and Systems* (IROS), 2010 IEEE/RSJ Int. Conf., 2010.
7. T. Kroger, F. M. Wahl, “Online trajectory generation: Basic concepts for instantaneous reactions to unforeseen events,” in *IEEE Trans. Robotics*, 2010, Feb., no. 1, pp. 94-111.

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PONGRATZ, Martin, Univ. Asst. (Institute of Computer Technology). Dipl.-Eng. (Higher Tech. School, Pinkafeld, 2002), MSc (Vienna Univ. of Technology, 2009). Researches: transport-by-throwing, robotic catching.

MIRONOV, Konstantin, Doctoral Stud. (Institute of Computer Technology). Dipl.-Eng., BSc (Ufa State Aviation Tech. Univ., 2012). Researches: material transportation by throwing and catching.

BAUER, Friedrich, Univ. Asst. (Institute of Computer Technology). Dipl.-Eng., MSc (1997), DSc (Vienna Univ. of Technology, 2001). Dissertation: "A modular concept for a distributed controller of simulators used for tribological analysis of total hip joint prostheses". Researches: digital systems, distributed controllers and simulators.