Detection of Mechanical Play of Revolute Robot Joint

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Abstract: This article introduces a method of detection of mechanical play of revolute joint based on recognition of impacts caused by the play. The method uses inexpensive acceleration measuring device with limited sampling frequency. The impact is recognized indirecly according to oscillation of mechanical oscilator. The method was tested on real servo drive Dynamixel AX-12A.

1 INTRODUCTION

In todays world robots equipped with manipulators are rather widespread and they are becoming still more casual. They are being used for tasks of many different kinds. Precise control of the robotic manipulator is essential for most of them. Controller of robotic manipulator has to deal with kinematic and dynamic properties and constraints of the manipulator and payload it carries. A lot of effort was invested into exploring areas of manipulator kinematics and dynamics with rather impressive results. Today there are software tools and simulators for simulation of manipulators forward kinematics and forward and backward dynamics like Gazebo (Koenig and Howard, 2004) or Webots (Michel, 2004), libraries of algorithms for solving inverse kinematics problem and planning trajectory of the motion for most of kinds of manipulators like OMPL (Şucan et al., 2012) and also tools that automate process of finding effective analytic inverse kinematics solvers for open kinematic chain manipulators (with some constraints) like OpenRAVE (Diankov, 2010).

Often used way of controlling a robotic manipulator is based on simulation. The controller has precise model of manipulator it controls and before it moves the real manipulator it finds and tests the motion with the simulated one. Controllers of this kind are rather robust and can be used with manipulators of many different kinds without need of changing their internal structure. Especially if they use planners and solvers based on iterative numerical algorithms.

Precision of controlers based on simulation is usually limited by conformity of model and real manipulator. Basic kinematic parameters of the manipulator - sizes of links, joint limits, link bounding objects - are usually available as a part of production documentation of manipulator and these values are usually precise. For measurement of manipulator dynamic parameters there are several algorithms like (Gautier M., Janot A., Vandanjon P.O., 2008) and others that provide results usually with good precision. Theoretically identification algorithms are limited only by precision of used sensors - mostly encoders in joints of robotic arm. Unfortunatelly precision of identification procedure aimed on obtaining parameters of robotic arm manipulator is limited by properties of the manipulator that are difficult to identify. One of them is mechanical play (backlash). Mechanical play is difficult to identify in general. Play can be hardly detected by joint encoder beacuse its resolution is usually limited. Identification is especially difficult if manipulator has encoders installed on joint motors instead of joint axis to increase resolution of position measurement. Disadvantage of this solution is that the mechanical play between gears of gearbox and play of bearings can not be measured by encoder. Anyway mechanical play is one of aspects that make difference between real manipulator and identified model.

2 MECHANICAL PLAY OF REVOLUTE JOINT

Most of robotic manipulators use at least one revolute joint. Revolute joints have evolved from simple joints with one degree of freedom (DOF) to two DOF joints with differential drive or three DOF robotic wrist (Meng Li, 2003). Play in revolte joints causes

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imprecision of end effector positioning. The longer the manipulator link is the more significant the effect of a play is. According to intallation of encoder there are two solutions used in revolute joints: with encoder connected with the motor and with encoder connected with joint axis. In a typical construction of articulated revolute joint the encoder is connected directly with the motor. In this construction play of gearbox can not be detected by encoder. This construction is modeled by model described in (Ahmad, 1985). Mechanical play in this model is given by gaps between teeth of gears, by play of bearings and also by dynamic deformation of gearbox. When motor of the joint starts to move it has to overcome gap caused by play so part of its motion is lost compared to output of encoder. This effect is called lost motion (Ahmad, 1985).

Another construction of articulated revolute joint typical for small servo drives uses high resolution encoder or potentiometer connected with joint axis. This solution is theoretically capable of detecting mechanical play of gearbox. If resolution of the encoder is high enought it is possible to detect play of arm link caused by gaps between gears by change of encoder value. Practically the play would have to be bigger than encoder step which can not be infinite small. For example in case of Dynamixel AX-12A servo drive (Collective of employees of ROBOTIS ComSchool ef Electrical Engineering, 2006) the encoder has 1024 steps per rotation which means that the lost motion would have to be more then or equal to 21' (angular minutes). This value multiplied by length of link connected to the joint gives us a length of an arc that end of link can traverse without noticing by encoder.

2.1 Model of Play between Two Spur Gears

Typically the most significant source of play in revolute robot joints are gaps between teeth of gears in gearbox of the joint. Play caused by spur gears is usually much bigger than play caused by bearings - especially in case of inexpensive servo drives. For this reason we decided to simplify model of play to model play caused by spur gears only. Model of force transmission between gears we use was presented in (R. Kalantari, 2009). For each pair of spur gears the model of contact force is following:

$$F_{cnt} = F_k + F_c = \beta \cdot \left(\frac{\Delta d}{d/2}\right)^n + \alpha \cdot \Delta v \cdot \left(\frac{\Delta d}{d/2}\right)^{n+1} \tag{1}$$

In equation 1 the F_k member is an elastic force and the F_c is a viscous force. The Δv is a difference of linear speed of gears at the point of contact, the Δd is a difference between linear positions of spur gears at the point of contact and the α and β coeficients are special constants that convert forces to proper size and unit. The exponent n is a large odd number.

In the model of spur gears the first gear is actuated by ideal actuator with no inertia, no backlash and infinite torque. This actuator changes position of the first gear with index 1. The second gears with index 2 is is actuated by the first gears through teeth with backlash. Force between teeth is described by equation 1. The F_{cnt} force causes angular acceleration of the second gear. The angular acceleration is given by inertia J_2 of the second gear and its radius R_2 according to equation 2.

$$\omega' = -\frac{\frac{F_{cnt}}{R_2}}{J_2}. \tag{2}$$

Change of position of particular tooth on each gear is given by corresponding relation in 3 where θ denotes angular position of particular gear.

$$p_1 = \theta_1 \cdot R_1; p_2 = \theta_2 \cdot R_2 \tag{3}$$

The shift between teeth of gears required for computation of the contact force F_{cnt} is described by equation 4. The difference between linear speeds of teeth at the point of contact of the gears is given by equation 5 in a similar way.

$$\Delta d = p_2 - p_1 \tag{4}$$

$$\Delta v = p_2' - p_1' \tag{5}$$

Response of the model of spur gears with play can be observed in figure 1. As input signal for the model the sine signal at frequency 6 Hz was used. The input signal controls angular position θ_1 of the first gear. It is a simplification that we can use thanks to ideal actuator with infinite torque so inertia of the first gear has no effect and we can neglect it.

In the figure we can see that the gaps between teeth cause visible peak in angular acceleration of the second gear. The peak in acceleration practically means that the contact of gears that are spinning each with different angular speed cause impact.

2.2 Current Methods of Measuring and Compensation of Mechanical Play

Currently the most of effort is aimed on elimination of the play itself. Elimination of mechanical play includes sophisticated design of gearbox and a very precise manufacturing of manipulator parts. Eliminating the play is absolutely the best solution. Unfortunately this solution is very expensive. It is usable for industrial manipulators which save a lot of money by doing mechanical work effectively and their higher

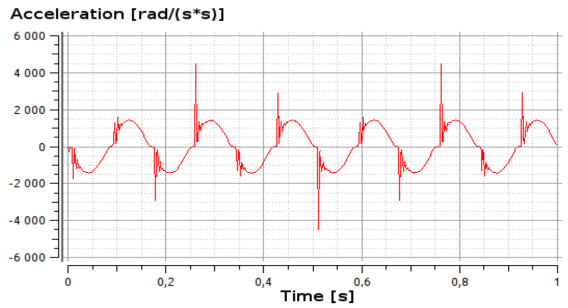

Figure 1: Response of spur gear model with backlash to sine excitation.

initial price is not a problem. But in case of experimental and prototype manipulators a high initial price is a serious problem. Experimental manipulators are usually built of inexpensive serial parts. They are usually equipped with common bearings and inexpensive joint drives. With such a low cost construction it is usually difficult to avoid mechanical play. Moreover there is also higher probability of quick wear out or mechanical damage of the manipulator. In case of low-cost experimental manipulators it is useful to be able to detect and measure mechanical play.

Measuring and compensation of mechanical play is described in (Ahmad, 1985) and (Hyun-Kyu Lim and Kang, 2009). In (Ahmad, 1985) imprecision of manipulator caused by several aspects including play is compensated according to feedback of human operator who measures total error of manipulator endpoint. The paper also presents procedure leading to excitation of mechanical play. The effect of play is mechanical overshoot of desired arm endpoint position. The overshoot can be converted into angular displacement of revolute joint and according to this displacement the compensating shift in motor angle is computed. To compensate properly the manipulator controller needs to keep a direction of previous motion to decide whether mechanical limit given by play was reached and which one.

In (Hyun-Kyu Lim and Kang, 2009) authors describe a method of measuring and compensation of mechanical play for industrial manipulator Hyundai HS165. The described method iteratively changes compensation parameters to minimize error between computed endpoint position and measured endpoint position. The paper also describes extention of the original method to include compensation of errors caused by stiffness of manipulator parts.

Both methods described above were developed for stationary industrial manipulators. They provide very precise compensation of errors caused by play and other aspects but they both require very precise measurement of end effector error. The measurement is done by measuring by hand (Ahmad, 1985) or by external sensors (Hyun-Kyu Lim and Kang, 2009). Unfortunatelly precise external measurement of endpoint position is usually rather difficult and expensive to realize. Measuring device has to be installed and precisely calibrated in relation to basepoint of the manipulator. It may cause difficulties especially in case of mobile robots where is usually not much space for proper installation of sensors measuring endpoint position. In this paper there is proposed an inexpensive and rather easy to establish method for detecting mechanical play based on impact detection.

3 DETECTION OF MECHANICAL PLAY

In the method proposed below the mechanical play is detected indirectly by detecting impacts caused by mechanical play between two moving spur gears in a gearbox. If there were no gaps between teeth of gears in the gearbox the input motion would be transferred to the output affected only by gear ratio. It means that the output trajectory would have the same shape as input one. If acceleration of the excitation motion is sine wave the output of the ideal gearbox would be also perfect sine wave. In real situation small gaps between teeth deform output acceleration trajectory as can be seen in figure 1. The peeks in acceleration caused by impact when teeth of the first gear meet the theeth of the second gear are easy to recognize in simulation but in real measurement it is not that easy to recognize them. The real measurement contains a lot of noise. The noise also contains peeks that can easily interfere with peeks caused by play so detection of play based on detection of peeks in acceleration would detect many false alarms. The solution we decided to use also uses the impact peeks but not directly. In proposed solution acceleration peeks shake a mechanical oscilator that starts to oscilate. The periodic oscilation of the known oscilator is then much easier to detect.

To model output of the oscilator we used standard model of damped oscillation described by equation 6. The model is based on principle of preservation of energy in isolated system. The m coeficient denotes a generalized mass, b is a breaking coeficient that is responsible for decreasing of amplitude in time, the k is a spring elasticity coeficient and the q is a generalized coordinate.

$$m \cdot q'' + b \cdot q' + k \cdot q = 0 \qquad (6)$$

This model was interconnected with model of spur gears with mechanical play described in prior section. The interconnection was done by adding acceleration

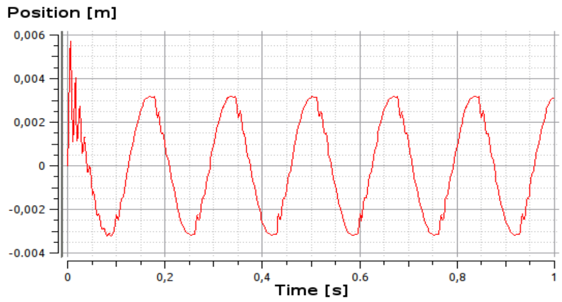

Figure 2: Position of free end of the mechanical oscillator.

caused by motion of the second gear to the acceleration in the equation 6. The oscilator is installed on a metalic bar connected with one end to the axis of the second spur gear in a direction orthogonal to the axis. The lenght of the bar is l and the ω_2 coeficient is angular acceleration of the second spur gear. Equation 7 describes extended damped oscillation model. Acceleration of the oscilator connected to the spur gear model with the same conditions that were used in previous section can be observed in figure 2.

$$m \cdot (q'' + \omega_2' \cdot l) + b \cdot q' + k \cdot q = 0 \tag{7}$$

In figure 2 appear small periodic waves in a sine trajectory of acceleration. These waves are caused by resonation of the oscilator.

Of course the oscillation of the oscilator causing fast small periodic change in acceleration mix with acceleration changes caused by motion of the second spur gear and with noise but it can be detected in spectrum. In spectrum it is possible to to filter out only the particular frequency - the resonation frequency of the oscilator - and omit all other frequencies. In spectrum the presence of oscillation of the oscilator can be detected by amplitude of the resonation frequency of the oscilator. Despite the theory that tells us that we can filter out only one particular frequency in real solution we have to filter out a small range of frequencies because due to dumping and some parts that shake in moment of impact the oscillation of the mechanical oscilator is not perfect. Processing of input signal is described by following equation. Output of the equation is a scalar value o that we can compare to some level value. If o is greater than level value impact is detected.

$$o = \sum \left(norm\left(fft(\vec{s_i}), f_{norm}, f_{norm\_w}\right) \odot \vec{mask} \right) \tag{8}$$

Where $\vec{s_i}$ is a vector of measured values, $\vec{mask}$ is a mask vector of ones and zeros and $norm$ is a normalization function that will be decribed later. When spectrum of input signal computed by fast Fourier transform from input vector is multiplied element by element by mask vector, only subsequence of spectrum is "selected" and the rest of elements of spectrum vector change to zero in result. Note that $\odot$ denotes a Hadamard (elementwise) product of vectors.

There are three parameters that can change behaviour of the method and setting their proper values is essential to reach good reliability. The first two parameters describe filter that extracts information about impact from the spectrum according to equation (10). These are frequency of resonation of measurement equipment f_{res} and width of detection window f_{width}. Effect of f_{res} is rather straightforward. The window width f_{width} on one hand should be wide enought to not to miss the peak that can become rather wide in real signals because of imperfect oscillation as desribed above but on the other hand it can not be too wide to receive noise. Third parameter that has significant impact on results of this method is the level value mentioned above that o_{scalar} is compared to. This level value has the same effect as detection levels in classificators. The level needs to be tuned to obtain the best ratio of proper detection to false positives and false negatives. The optimisation equation for level value is following:

$$level = \\ = argmax_x \left(\frac{correct\_accept(eval(f_{res}, f_{width}, ss, x))}{false\_positive(eval(f_{res}, f_{width}, ss, x))} + \frac{correct\_reject(eval(f_{res}, f_{width}, ss, x))}{false\_negative(eval(f_{res}, f_{width}, ss, x))} \right) \tag{9}$$

Function $eval(X,Y,Z)$ is a funtion that evaluates runs of the method described above. It runs with sample set ss and with constant properly set parameters f_{res} and f_{width} and level x which is object of optimisation. The function returns a matrix of result values of correctly accepted samples (play detected), correctly rejected samples (play not detected) and false positive and false negative detections. Functions $correct\_accept$, $false\_positive$ and others are functions that return value they describe by their name from the result matrix.

The $\vec{mask}$ vector compounds of $mask_i$ components. According to resonation frequency of oscilator f_{res} and width of detection range f_{width} each coeficient of masking vector is computed. The computation is defined by following equation. Function $freq\_fft$ converts real frequency to coeficients of fast Fourier transform [1].

[1] The function $freq\_fft$ in equation (10) would require also sampling frequency and cardinality of input vector as arguments but for better readability of the equation these parameters were omitted.

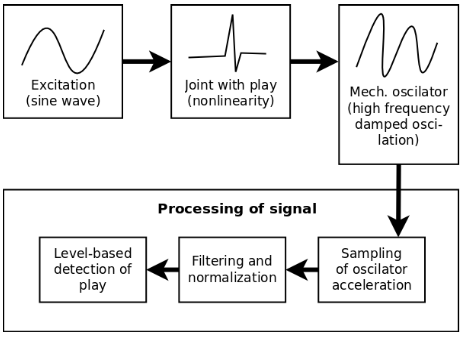

Figure 3: Block diagram of entire solution.

$$mask_i = \begin{cases} 1, i \in < freq\_fft(f_{res} - f_{width}/2)), \\ \qquad freq\_fft(f_{res} + f_{width}/2)) > \\ 0, \text{otherwise} \end{cases} \tag{10}$$

Function *norm* is normalization function. This function normalizes each sample of spectrum by normalization coeficient. Normalization coeficient is computed as average of subsequence of amplitude values extracted from spectrum. The f_{norm} argument defines frequency which will be the center of subsequence extracted from vector of spectrum. Length of the sequence is defined by f_{norm_w}. Average of the extracted sequence is used as normalization value that divides each element of spectrum vector. Function *norm* returns vector of normalized values of spectrum. Complete solution can be observed in figure 3.

As a mechanical oscilator can be theoretically used any object that will resonate after impact. Theoretically the manipulator links themself could be used as oscilators but practically there are some shortcomings. Usually the robotic manipulator links are robust and have complicated shape. Due to it manipulator links have usually very high and hardly predictable resonation frequency and its resonation is quickly attenuated so detector of oscillation would have to be extremly sensitive. The sensitivity of the detector brings a serious problem with noise. This can be solved by using properly formed metal bar as the oscilator. We used a metal bar installed on manipulator link in direction parallel to direction of manipulator link - one end is fixed on the manipulator link and the other free end connected with acceleration sensor. When impact occurs the metal bar starts to oscilate like if it was hit by gavel. This way it is possible to capture oscillation of metal bar when impact occurs in joint of manipulator. Moreover we can change resonation frequency and intensity of oscillation by changing shape of the metal bar.

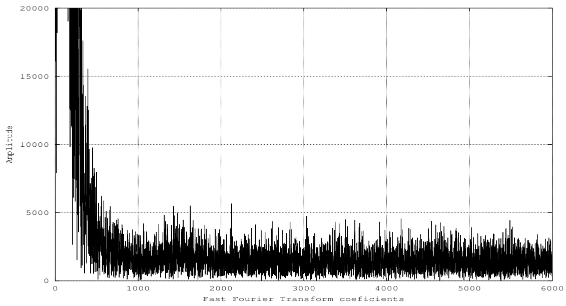

Figure 4: Spectrum of acceleration during motion without impact.

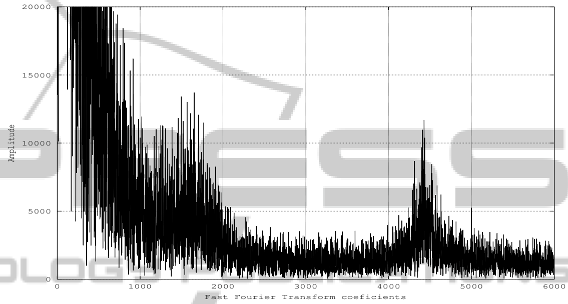

Figure 5: Spectrum of acceleration during motion with impact.

4 EXPERIMENTS AND RESULTS

Initial experiments were done on special experimental apparatus that is from mechanical point of view very similar to metal bar with one end fixed to revolute joint and the other end free. To simulate play the metal bar could rotate between two blocks that limit its revolute motion - one fixed and the other configurable. The entire apparatus rotates about the same axis as the metal bar inside it does. This apparatus was useful to prove the concept proposed in prior section but its mechanical concept is still rather different from real joint and links of manipulator. The apparatus demonstrates change in the spectrum when play appears as is visualized in figures 4 (without play) and 5 (with play).

To prove correctness of principle of the method it was necessary to execute experiments on a real robotic joint. A simple robot compounding of two links connected together by AX-12 revolute servo drive was used as experimental device. One link was a fixed base link and the other was free link. On the free link there was installed measuring device - metal bar with acceleration sensor. One end of metal bar was mounted on the free link and the other end with acceleration sensor was free.

The servo drive has a small play. During the test-

Table 1: Results of experimenting with real revolute joint AX-12 servo drive.

Play	True pos. [%]	False neg. [%]
With play	98	2
W/o play	100	0

ing it was necessary to obtain also samples without play. To ensure that the conditions for the measurement of motion with play and without play will be the same a small trick was used. The servo drive was not used as a motivator. Base link of the experimental robot was actuated so entire experimental robot was moving. To test detection of mechanical play the robot was straightened and the servo drive was configured to keep its position. The entire robot was waved in direction perpendicular to the axis of servo drive and to the common axis of both links so mechanical play of the servo drive was excited. To test motion without mechanical play the servo drive was bypassed by mounting two links of robot together by solid metalic part so the servo drive could not move anymore. Other difficulty was the actuator itself. It was necessary to actuate entire robot by actuator without its own play. As a simple solution of actuator without play human hand was used. Human hand can hardly generate perfectly periodic motion but for this experiment it was not essential because impacts appear every time the acceleration changes its direction.

Results of the experiment are shown in table 1. The true positive in the table 1 means that the property was detected correctly. The false negative means that the property was not detected despite it was present in the sample. False positive is not present in the table beacause the properties are in mutual exclusive relation so false negative of one property is false positive of the other.

5 CONCLUSION

In this paper a method of detection of mechanical play based on impact recognition was proposed. The method in proposed form is usable for revolute joints only. Theoretical principles were tested on real joint based on Dynamixel AX-12A servo drive. Experiments prove that the method is usable for distinguishing between motion of servo drive with play and without play. Reliability of detection was not perfect.

There are still several problems that need to be solved in the future before the method will be usable in common use cases. Extending this method to robots with more than one degree of freedom bring a problem of distiguishing between sources of the play - especially if there are two joints with parallel axes. Another problem is automatized way of finding proper values for the parameters of the method and also proper value of acceleration of the excitation motion. It would be also very useful to extend the method to not only detect the mechanical play but also measure the size of mechanical play.

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REFERENCES

Ahmad, S. (1985). Second order nonlinear kinematic effects and their compensation. *School ef Electrical Engineering, Purdue University*.

Collective of employees of ROBOTIS ComSchool ef Electrical Engineering, P. U. (2006). *Dynamixel AX-12 User's Manual*. ROBOTIS Company.

Diankov, R. (2010). Automated construction of robotic manipulation programs. Carnegie Mellon University, Robotics Institute, CMU-RI-TR-10-29, http://www.programmingvision.com/rosen_diankov_thesis.pdf.

Gautier M., Janot A., Vandanjon P.O. (2008). Didim: A new method for the dynamic identification of robotsfrom only torque data. In *IEEE International Conference on Robotics and Automation,*. Pasadena, CA, USA.

Hyun-Kyu Lim, Dong-Heyok Kim, S.-R. K. and Kang, H.-J. (2009). A practical approach to enhance positioning accuracy for industrial robots. *IROS-SICE International Joint Conference*.

Koenig, N. and Howard, A. (2004). Design and use paradigms for gazebo, an open-source multi-robot simulator. In *In IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2149–2154.

Meng Li, Tian Huang, Z. L. (2003). Conceptual design and kinematic analysis of 3-dof robot wrist. *International Conference on Robotics & Automation*.

Michel, O. (2004). Professional mobile robot simulation. *International Journal of Advanced Robotic Systems*, 1(4):39–42. Commercial Mobile Robot Simulation Software.

R. Kalantari, M. S. F. (2009). Backlash nonlinearity modeling and adaptive controller design for and electromechanical power transmission system. *Mechanical Engineering*, 16(6):463 – 469.

Şucan, I. A., Moll, M., and Kavraki, L. E. (2012). The Open Motion Planning Library. *IEEE Robotics & Automation Magazine*, 19(4):72–82. http://ompl.kavrakilab.org.