UDK 681.586:007.52

Zmanjšanje nedoločenosti lege in usmerjenosti predmeta v prijemalu robota

Reducing Uncertainty in Position and Orientation of Object in Robot Gripper

STANKO DOLENŠEK

0. UVOD

Človek je prek svojih čutil nenehno povezan z okolico. Na podlagi zaznav se ustrezno odzivamo in načrtujemo nova delovanja. Po izkušnjah lahko isto čutilo uporabljamo v različne namene, ali pa dosežemo enako zaznavo z različnimi čutili. To je velika prednost v primeru okvare katerega od čutil, ker ga lahko s preostalimi čutili vsaj delno nadomestimo. Če izgubimo vid, si lahko pomagamo s tipom in sluhom.

V robotiki se želimo v največji meri približati vsem človeškim lastnostim in tako zgraditi čimbolj samostojne robote. Na področju povezovanja zaznaval raziskujejo nove uporabne možnosti že znanih zaznaval (senzorjev). Pri tem je pomembno tudi povezovanje različnih zaznaval z namenom, da bi dobili nove podatke o okolju. Bistvena prednost je, če lahko isto zaznavalo uporabljamo za različne naloge. Tako ob enakih učinkih potrebujemo manj zaznaval, poenostavimo celoten robotski sistem in zmanjšamo stroške.

1. RAZPOZNAVANJE PREDMETOV MED DELOVANJEM

Ravnanje s predmeti je osnovna robotska naloga. Čas med opravljanjem gibov lahko koristno uporabimo za določena merjenja. Z zaznavali lahko ugotavljamo lego in usmerjenost predmeta v prijemalu, predmet lahko stehtamo, ugotavljamo nepravilnosti, določamo barvo. Pri tem s pridom uporabimo spoznanja iz preučevanja človeka.

Človek lahko s tipom in zaznavanjem obremenitev ugotavlja tudi zelo zahtevne stvari. Vzemimo za primer zaprto posodo, v katero ne moremo prodreti s pogledom. Posodo lahko potežkamo, jo premikamo sem in tja, obračamo, potresamo. Iz tega ugotovimo, ali je posoda prazna ali polna. Lahko sklepamo o vsebini posode: v njej je tekočina, sipka snov, bolj groba snov, kroglice ali oglati predmeti, en predmet ali več predmetov. Obenem si lahko pomagamo tudi s sluhom. Z otipavanjem določimo obliko posode. S prehajanjem toplote iz roke na posodo sklepamo, ali je posoda kovinska oziroma nekovinska.

0. INTRODUCTION

A human being with his organs of sense continually communicates with the environment. This is the base of executing suitable reactions and planning new actions. With some experience we can use the same organ of sense for various purposes or we achieve the same perception with different organs of sense. This is a great advantage in the case of a damaged organ of sense, because we could partially substitute it with the remaining organs of sense. In the case of loosing our ability to see we can use our hearing and touch.

In robotics we want to approach all human qualities on a large scale as to build autonomous robots. In the field of sensor integration research has been carried out concerning some new usages of the existing sensors. Here it is important to connect different sensors in order to get some new information about the environment. It is of great advantage to use the same sensor for different tasks. In that way we need less sensors to obtain the same effect, the whole robot is less complicated and costs are lower.

1. RECOGNITION OF OBJECTS DURING MANIPULATION

Manipulating objects is the main task of a robot. The time during manipulation can be used for some measurements. By the sensors we can find out the position and the orientation of the object in the robot gripper, we can weigh the object, then we can find out some irregularities and colour of the object. Here we can take full advantage of recognitions from studying human beings.

By touch and force sensing, person can find out very complicated things. For example, let us take a covered dish the inside of which we can' t see. We can weigh the dish in our hand, move it to and from, turn it round or shake it. When performing all these movements we find out whether the dish is empty or if there is something inside. We can infer about the contents of the dish: it could be liquid, powdered or granulated material, spherical or angular objects, one object or more. At the same time we can use our hearing. By touching the dish we determine its shape. By heat transition from the dish to our hand we can find out the kind of material: either it is metal or not.

Določena dela bolje opravimo, če predmet, s katerim delamo, pravilno primemo. Najugodnejši prijem je navadno v bližini težišča. Pri tem dosežemo boljši izkoristek pri porabi energije, večjo dinamiko delovanja, ugodnejše statične in dinamične obremenitve prijemala. Primer je nošnja težje palice. Veliko laže držimo tak predmet na sredini kakor na koncu. Na sredi palice je težišče in zato v roki ne čutimo nobenih dodatnih statičnih momentov. Tako ugotovimo tudi težišče predmeta.

Povezavo med dvema predmetoma preverimo tako, da ju potresemo in pri tem ugotavljamo, ali se premikata. Masa predmeta je lastnost, ki pomaga pri razpoznavanju. S tehtanjem med množico predmetov z znanimi masami ugotovimo, kateri predmet je v prijemalu. Če predmet nima prave mase, je lahko poškodovan, ima presežek materiala ali pa sploh ni pravi.

2. STATIČNO DOLOČANJE LEGE PREDMETA V PRIJEMALU

Osnova za določanje lege predmeta v prijemalu bo uporaba zaznavala sil in momentov v zapestju robota. Zamisel se mi je porodila ob prebiranju strokovnega članka avtorjev Tsujimure in Yabute [1] in opisanih razmišljanjih. Podobno so An, Atkenson in Hollerbach [3] uporabili zaznavala sil in momentov za določanje težišča in vztrajnostnega momenta neznanega bremena.

Imamo robota s prijemalom. Med prijemalom in zadnjim segmentom robota je vgrajeno zaznavalo sil in momentov. Koordinatni sistem zaznavala bo osnova za vse nadaljnje izvajanje (sl. 1).

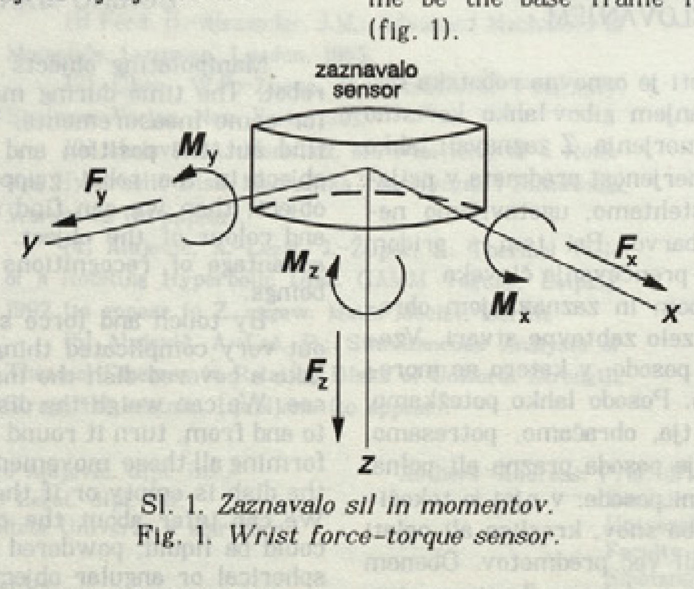
Some tasks are performed better when the manipulating object is grasped in the right way. The most favourable grasp is usually the one in the centre of gravity. Thus we make good use of energy, get better dynamics of manipulation, more favourable static and dynamical charge of the gripper. For example, we take a heavy stick. We can grasp this object in the middle much easier than at the end. In the middle of the stick there is a centre of gravity and we don't sense any static torque in our hand. Or else we can find the centre of the stick's gravity.

The connection between two objects could be checked by shaking them. Thus we find out whether they move towards each other. The mass of the object is the characteristic that can help us with its recognition. By weighing a set of objects with known masses, we find out which object we have grasped. Furthermore, if the object is not of the proper mass, there is something wrong: it could contain either too much material, be damaged or it is not the right one.

2. STATIC DETERMINATION OF OBJECT POSITION IN ROBOT GRIPPER

We take a wrist force-torque sensor for determining object position in the robot gripper. I came across the idea when I read a paper by Tsujimura and Yabuta [1] and when I thought over the things I had written in the first chapter. Similarly the authors An, Atkenson and Hollerbach [3] used a force-torque sensor for determining the mass centre and the inertia for an unknown load in the robot gripper.

Let us take a robot with a gripper. There is a wrist force-torque sensor between the gripper and the last robot joint. Let the wrist sensor frame be the base frame for further explanation (fig. 1).



Sl. 1. *Zaznavalo sil in momentov.*
Fig. 1. *Wrist force-torque sensor.*

Vzemimo, da robot v prijemalu drži predmet, katerega geometrična oblika je znana. Težišče predmeta v koordinatnem sistemu zaznavala določa lego predmeta.

Let us assume there is an object with known geometry in the robot gripper. Object position is determined by its centre of mass.

Predmet in prijemalo s svojima težama povzročata moment na zaznavalo sil in momentov. Moment M_s, ki ga izmeri zaznavalo, je vsota dveh momentov. Prvi moment povzroča teža prijemala T_p, drugega pa teža predmeta oziroma objekta T_o:

The masses of the object and the gripper cause static torque to the wrist sensor. The static torque M_s, which is measured by the wrist sensor, is the sum of two torques. The first torque is caused by the object weight T_o and the second one by the gripper weight T_p:

$$M_s = M_p + M_o \tag{1}$$

Moment prijemala lahko zapišemo kot vektorski produkt:

The gripper torque could be expressed as vector product:

$$M_p = r_p \times T_p \tag{2}$$

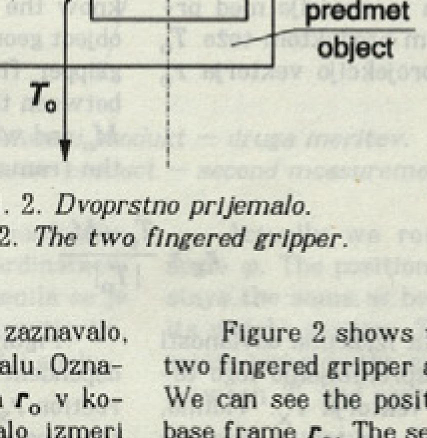
Ročica r_p je vektor, ki kaže lego težišča prijemala v koordinatnem sistemu zaznavala. Ustrezno lahko zapišemo moment M_o, ki ga v zaznavalu povzroča predmet (objekt):

The handle r_p is a vector which determines the gripper centre of mass position in the base frame. Similarly we can express the object torque influence M_o in our wrist sensor:

$$M_o = r_o \times T_o \tag{3}$$

Ročica r_o pomeni lego težišča predmeta v koordinatnem sistemu zaznavala in je v našem primeru neznana. Pri izračunu r_o z uporabo T_o in M_o naletimo na težavo [1], ker vektorski produkt ne ohranja informacije o kotu med ročico in silo.

The handle r_o is a vector which determines the object centre of mass position in the base frame. In our example it is unknown. If we want to compute r_o from T_o and M_o, we have a problem [1] because the vector product doesn' t preserve the information about the angle between the handle and the force.



Sl. 2. *Dvoprstno prijemalo.*
Fig. 2. *The two fingered gripper.*

Slika 2 prikazuje stranski pogled na zaznavalo, dvoprstno prijemalo in predmet v prijemalu. Označen je tudi vektor lege težišča predmeta r_o v koordinatnem sistemu zaznavala. Zaznavalo izmeri F_s, ki je teža predmeta in prijemala skupaj. Ker težo prijemala poznamo, lahko izrazimo težo predmeta:

Figure 2 shows the side view at the sensor, two fingered gripper and the object in the gripper. We can see the position vector of an object in a base frame r_o. The sensor measures the force F_s, which is the weight of both; the sensor and the object. As we know the gripper weight, we can compute the object weight:

$$T_o = F_s - T_p \tag{4}$$

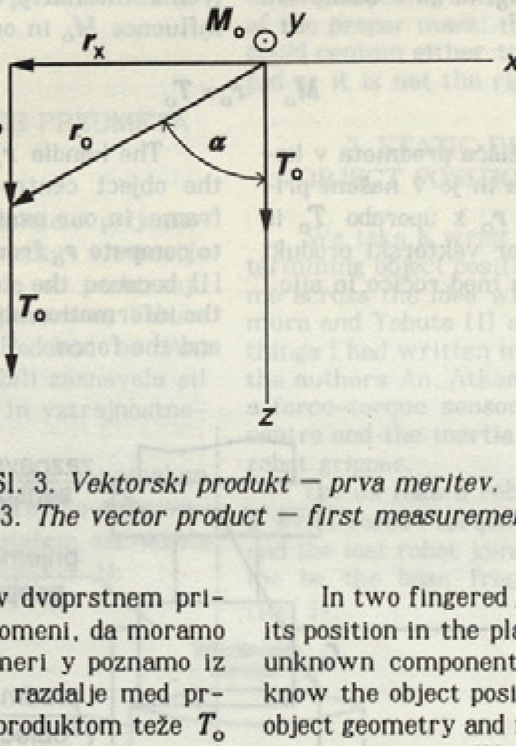
Druga veličina, ki jo izmerimo z zaznavalom, je moment M_s. Izraz (2) vsebuje znane veličine r_p in T_p, zato ostane v izrazu (1) edina neznanka moment predmeta M_o:

The second magnitude measured by wrist sensor is the torque M_s. In the equation (2), magnitudes r_p and T_p are known. The object torque M_o is the only unknown quantity in the equation (1):

$$M_o = M_s - r_p \times T_p \qquad (5).$$

Predmet v prijemalu lahko sedaj obravnavamo popolnoma ločeno od vplivov prijemala na zaznavalo (sl. 3). Teža predmeta T_o povzroča zaradi vektorja lege r_o v zaznavalu moment M_o. Teža predmeta T_o in vektor r_o oklepata kot α ter sta pravokotna na moment M_o.

Now we can handle the object in the gripper completely from the gripper influence to the wrist sensor (fig. 3). The object weight T_o causes, by means of the position vector r_o, the torque M_o to the wrist sensor. The angle between T_o and vector r_o is α; and both values are rectangular to the torque M_o.



Sl. 3. *Vektorski produkt — prva meritev.*
Fig. 3. *The vector product — first measurement.*

Vektor r_o lahko zavzame v dvoprstnem prijemalu lego v ravnini x-z. To pomeni, da moramo določiti dve neznanki. Lego v smeri y poznamo iz geometrične oblike predmeta in razdalje med prstoma prijemala. Z vektorskim produktom teže T_o in momenta M_o dobimo le projekcijo vektorja r_o na koordinatno os x:

In two fingered gripper the vector r_o can take its position in the plain x-z. This means that two unknown components are to be determined. We know the object position in direction y from the object geometry and from the distance between the gripper fingers. We compute the vector product between the object weight T_o and the object torque M_o and we get only the projection of vector r_o to the frame axis x:

$$r_x = \frac{T_o \times M_o}{|T_o|^2} \qquad (6)$$

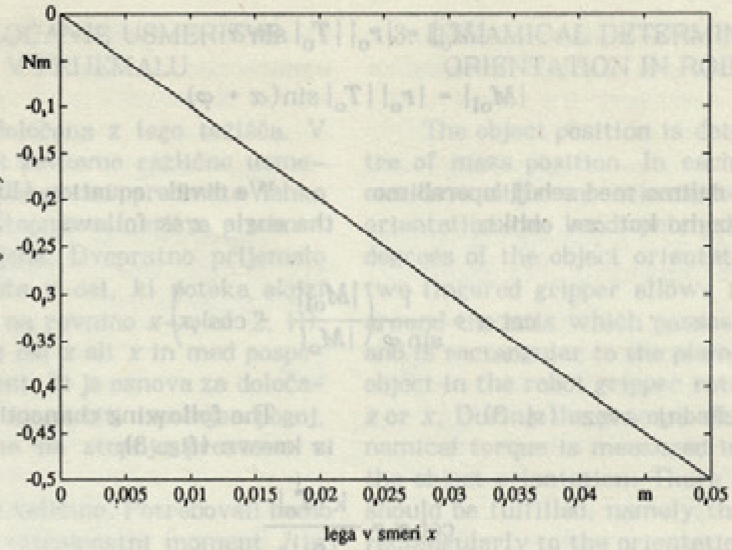
Slika 4 prikazuje rezultat izračuna odvisnosti statičnega momenta M_o, če spreminjamo lego težišča predmeta r_o v smeri vektorja r_x. Vidimo, da velja med velikostma obeh vektorjev linearna zveza, kar je zelo ugodno.

Vektor lege težišča izrazimo kot vsoto vektorjev r_x in k T_o:

Figure 4 shows how the static torque M_o is dependent of the changing object position r_o in direction r_x. We can see linear connection between the magnitudes of both vectors. That is favourable.

We can compute the position vector r_o from the sum of the vectors r_x and kT_o:

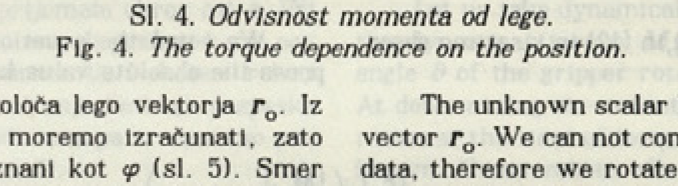
$$r_o = r_x + k\,T_o \qquad (7)$$



Sl. 4. *Odvisnost momenta od lege.*
Fig. 4. *The torque dependence on the position.*

Neznani skalar k določa lego vektorja $\boldsymbol{r}_o$. Iz znanih podatkov ga ne moremo izračunati, zato zavrtimo prijemalo za znani kot φ (sl. 5). Smer vrtenja mora biti pravokotna na os y. Opravimo še eno meritev momenta $\boldsymbol{M}_{s1}$. Ko izračunamo in odštejemo moment prijemala, dobimo moment $\boldsymbol{M}_{o1}$, ki ga povzroča predmet na zaznavalo.

The unknown scalar k determines the position vector $\boldsymbol{r}_o$. We can not compute it from the known data, therefore we rotate the gripper by a known angle φ (fig. 5.) The direction of rotation must be rectangular to the axis y. Then we make the second torque measurement $\boldsymbol{M}_{s1}$. After computing and subtracting the griper torque we obtain the object torque $\boldsymbol{M}_{o1}$.



Sl. 5. *Vektorski produkt – druga meritev.*
Fig. 5. *The vector product – second measurement.*

Za kot φ smo pravzaprav zavrteli koordinatni sistem zaznavala. Lega vektorja $\boldsymbol{r}_o$ v koordinatnem sistemu je ostala nespremenjena. Spremenila se je lega teže $\boldsymbol{T}_o$, ker je teža obdržala smer gravitacije. Kot med vektorjem $\boldsymbol{r}_o$ in težo $\boldsymbol{T}_o$ je sedaj enak:

Actually we rotate the base frame by the angle φ. The position vector $\boldsymbol{r}_o$ in the base frame stays the same as before rotation. It has changed its weight position $\boldsymbol{T}_o$ because the weight always points towards the direction of gravity. The angle between $\boldsymbol{T}_o$ and vector $\boldsymbol{r}_o$ is now equal:

$$\sphericalangle(\boldsymbol{r}_o, \boldsymbol{T}_o) = \alpha + \varphi \qquad (8).$$

Absolutne vrednosti momentov $\boldsymbol{M}_o$ in $\boldsymbol{M}_{o1}$ lahko izrazimo tudi z absolutnimi vrednostmi vektorjev $\boldsymbol{r}_o$ in $\boldsymbol{T}_o$ ter kotom med njima:

The absolute values of torques $\boldsymbol{M}_o$ and $\boldsymbol{M}_{o1}$ can be put down as absolute values of the vectors $\boldsymbol{r}_o$ and $\boldsymbol{T}_o$ and the angle between them (9), (10):

$$|M_o| = |r_o|\,|T_o| \sin\alpha \tag{9}$$

$$|M_{oI}| = |r_o|\,|T_o| \sin(\alpha + \varphi) \tag{10}$$

Izraza (9) in (10) delimo med seboj, uporabimo adicijski izrek in izrazimo kot α v obliki:

We divide equation (10) with (9) and express the angle α as follows:

$$\cot\alpha = \frac{1}{\sin\varphi}\left(\frac{|M_{oI}|}{|M_o|} - \cos\varphi\right) \tag{11}$$

Poznamo tudi naslednjo zvezo (sl. 3):

The following connection between the vectors is known (fig. 3):

$$\cot\alpha = \frac{k\,|T_o|}{|r_x|} \tag{12}$$

Izenačimo izraza (11) in (12) in izrazimo absolutno vrednost $k\,T_o$:

We equal the equation (11) and (12) and express the absolute value $k\,T_o$:

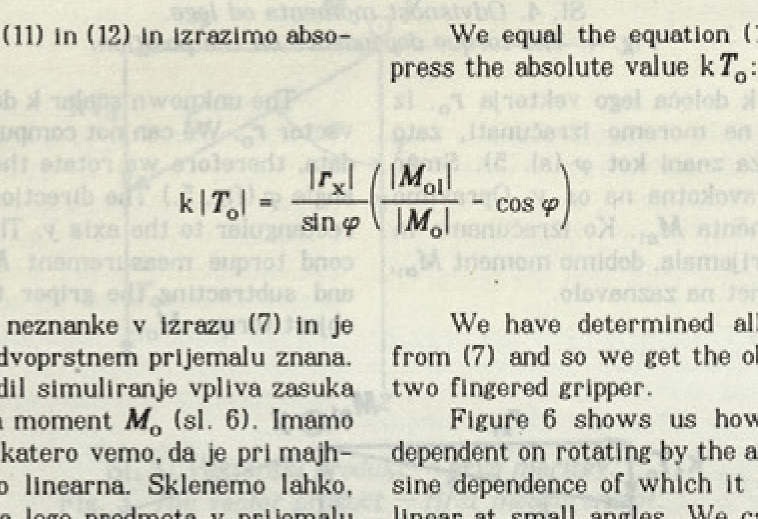
$$k\,|T_o| = \frac{|r_x|}{\sin\varphi}\left(\frac{|M_{oI}|}{|M_o|} - \cos\varphi\right) \tag{13}$$

Določili smo vse neznanke v izrazu (7) in je tako lega predmeta v dvoprstnem prijemalu znana.

Izraz (13) je potrdil simuliranje vpliva zasuka prijemala za kot φ na moment M_o (sl. 6). Imamo sinusno odvisnost, za katero vemo, da je pri majhnih zasukih praktično linearna. Sklenemo lahko, da je točnost določanja lege predmeta v prijemalu neposredno odvisna le od zaznavala sil in momentov.

We have determined all unknown vectors from (7) and so we get the object position in the two fingered gripper.

Figure 6 shows us how the torque M_o is dependent on rotating by the angle φ. We have got sine dependence of which it is known that it is linear at small angles. We can conclude that the accuracy of determining the object position is directly dependent only on the wrist sensor.



Sl. 6. *Vpliv zasuka prijemala na moment.*

Fig. 6. *Dependence of the torque M_o from the turn round angle φ.*

3. DINAMIČNO DOLOČANJE USMERITVE PREDMETA V PRIJEMALU

Lega predmeta je določena z lego težišča. V vsaki legi lahko predmet zavzame različne usmeritve. Nedoločenost v usmeritvi predmeta lahko odpravimo z dinamiko. Stopnje usmeritve predmeta v prijemalu so omejene. Dvoprstno prijemalo dopušča vrtenje predmeta v osi, ki poteka skozi težišče in je pravokotna na ravnino z-x (sl. 2, 11). Predmet zavrtimo okrog osi z ali x in med pospeševanjem merimo moment, ki je osnova za določanje usmeritve. Pri tem mora biti izpolnjen pogoj, da je vrtenje pravokotno na stopnjo prostosti v usmeritvi.

Vpeljimo dinamične veličine. Potrebovali bomo dinamični moment M_d, vztrajnostni moment J in kot ϑ, ki je kot vrtenja prijemala okrog osi z. Pri določanju usmeritve bomo morali poznati kotni pospešek v času merjenja momenta. Nekateri roboti ponujajo možnost programiranja kotnega pospeška pri vrtenju prijemala. Večinoma pa si moramo pomagati z zunanjimi zaznavali.

Zaznavalo izmeri moment M_s, ki je vsota statičnega momenta M_{ss} in dinamičnega momenta M_{ds}:

3. DYNAMICAL DETERMINING OF OBJECT ORIENTATION IN ROBOT GRIPPER

The object position is determined by the centre of mass position. In each position the object can have different orientations. Uncertain object orientation can be dispatched by dynamics. The degrees of the object orientation are limited. The two fingered gripper allows rotation of an object around the axis which passes the centre of mass and is rectangular to the plain z-x (fig's 2, 11). The object in the robot gripper rotates around the axes z or x. During the process of acceleration the dynamical torque is measured in order to determine the object orientation. There is one condition that should be fulfilled, namely the object must rotate rectangularly to the orientation degree of freedom.

Let us take dynamical magnitudes. We' ll take the dynamical torque M_d, the inertia J and the angle ϑ of the gripper rotation around the axis z. At determining the orientation, the angle acceleration at the time of torque measurement must be known. Some robots allow programming of the angle acceleration at the gripper rotation. But we mostly have to use additional sensors.

The wrist sensor measures the torque M_s, which is the sum of the static torque M_{ss} and the dynamical torque M_{ds}:

$$M_s = M_{ss} + M_{ds} \qquad (14).$$

Statični moment poznamo že iz drugega poglavja in se sedaj pojavlja kot znana veličina. Sestavljata ga statična momenta prijemala M_{sp} in predmeta v prijemalu M_{so}:

The static torque is known from the second chapter. The static torque is the sum of the static torque of the gripper M_{sp} and static torque of the object M_{so}:

$$M_{ss} = M_{sp} + M_{so} \qquad (15).$$

Dinamični moment M_{ds} (16) povzročajo zaznavalo, prijemalo in predmet v prijemalu s svojimi vztrajnostnimi momenti v času, ko je kotni pospešek različnen od nič:

The dynamical torque M_{ds} (16) is caused by the inertia of the wrist sensor, the gripper and the object in gripper when the angle acceleration is not equal to zero:

$$M_{ds} = M_{dsenz} + M_{dp} + M_{do} \qquad (16).$$

Dinamični moment zaznavala M_{dsenz} poznamo. Zapišemo ga kot zmnožek vztrajnostnega momenta zaznavala J_s in kotnega pospeška:

The dynamical torque of the sensor M_{dsens} is known. We can write it as a product of the inertia J_s and the angle acceleration:

$$M_{dsenz} = J_s \ddot{\vartheta} \qquad (17).$$

Ustrezno lahko pišemo tudi dinamični moment M_{dp} prijemala:

Analogously the dynamical torque of gripper M_{dp} could be expressed as follows:

$$M_{dp} = J_p \ddot{\vartheta} \qquad (18).$$

Edina neznana veličina je dinamični moment M_{do} predmeta v prijemalu in ga lahko izračunamo:

Now the only unknown magnitude is the dynamical torque M_{do} of the object in the griper. It can be computed:

$$M_{do} = M_s - M_{ss} - M_{dsenz} - M_{dp} \quad (19).$$

Dinamični moment M_{do} predmeta v prijemalu je odvisen od vztrajnostnega momenta predmeta J_o in kotnega pospeška:

The dynamical torque of the object in gripper M_{do} is dependent on the object inertia J_o and the angle acceleration:

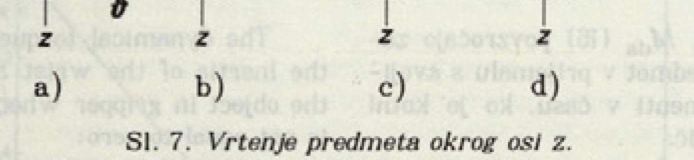
$$M_{do} = J_o \ddot{\vartheta} \quad (20).$$

V izrazu (20) se pojavlja vztrajnostni moment J_o kot neznana veličina, ker ne poznamo prave usmeritve predmeta v prijemalu.

Slika 7 prikazuje vpliv usmeritve predmeta na njegov vztrajnostni moment. Čim bliže osi vrtenja je razporejena masa predmeta, manjši vztrajnostni moment ima (sl. 7a). Če predmet spremeni usmeritev pravokotno glede na os vrtenja z, se vztrajnostni moment povečuje in doseže največjo vrednost, ko je masa najbolj oddaljena od osi (sl. 7b, c). V teh primerih je bilo težišče predmeta na osi vrtenja. Predmet je lahko tudi odmaknjen od osi vrtenja (sl. 7d), kar tudi vpliva na vztrajnostni moment. Večji ko je odmik, večji bo vztrajnostni moment.

In the equation (20) the object inertia is presented as an unknown magnitude because we don't know the real object orientation in the robot gripper.

Figure 7 shows the influence of the object orientation on the object inertia. The closer the mass of the object to the rotation axis the lower inertia it causes (fig. 7a). If the object changes its orientaion rectangular to the rotation axis z, then the object inertia is getting higher and reaches its maximum value when the mass is farthest from the rotation axis (fig. 7b and 7c). In the upper two cases the object centre of the mass lies on the rotation axis. The rotated object can also be removed from the rotation axis (fig. 7d), which influences the inertia as well. The bigger the remoteness the bigger the inertia.



Sl. 7. *Vrtenje predmeta okrog osi z.*

Fig. 7. *Rotating of the object around the axis z.*

Vztrajnostni moment predmeta okrog osi z lahko popišemo z naslednjim izrazom:

The object inertia – when rotating around the axis z – can be expressed by the equation:

$$J_o = \int x^2 d\, m \quad (21).$$

V primerih, ko je predmet odmaknjen od osi vrtenja, si pri integraciji (21) pomagamo s Huygens–Steinerjevim pravilom:

When the object is shifted from the rotation axis, we can compute the integral equation (21) according to the Huygens–Steiner rule:

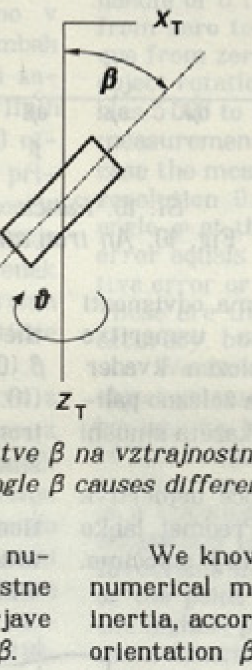
$$J_o = J_{oT} + r^2 m \quad (22).$$

Prvi člen je vztrajnostni moment predmeta J_{oT} s težiščem na osi vrtenja. Drugi člen določa povečanje vztrajnostnega momenta, če je težišče predmeta za razdaljo *r* oddaljeno od osi vrtenja, *m* pomeni maso predmeta. Maso predmeta in razdaljo *r* poznamo iz statičnega določanja lege predmeta v prijemalu.

Celoten problem določanja usmeritve predmeta smo prevedli na izračun vztrajnostnega momenta predmeta s težiščem na osi vrtenja (sl. 8).

The J_{oT} stands for the object inertia when the object's centre of mass is on the rotation axis. The second term expresses the increase of the object inertia when the object is shifted from the rotation axis by the value *r*. And *m* stands for the mass of the object. The distance *r* and the mass *m* are known from static determination of object position in the robot gripper.

determination of the object orientation is being reduced to the computing of object inertia when its centre of mass is on the rotation axis (fig 8).

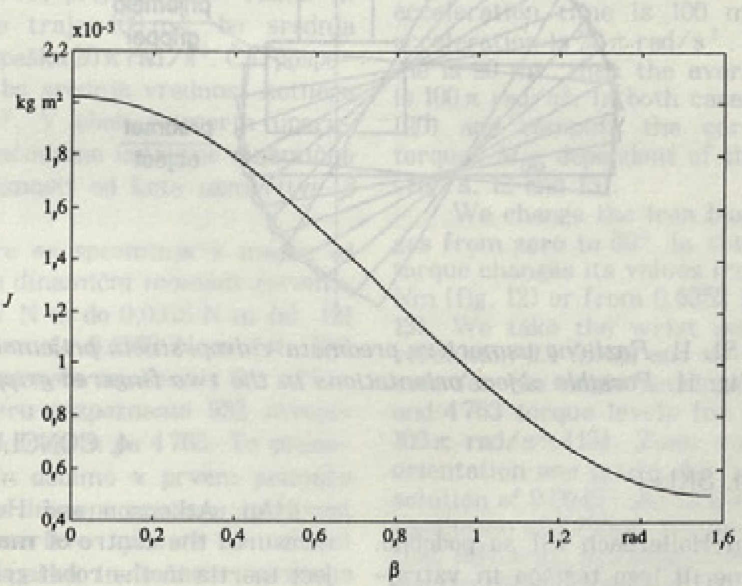


Sl. 8. *Vpliv usmeritve β na vztrajnostni moment.*

Fig. 8. The orientation angle β causes different object inertia.

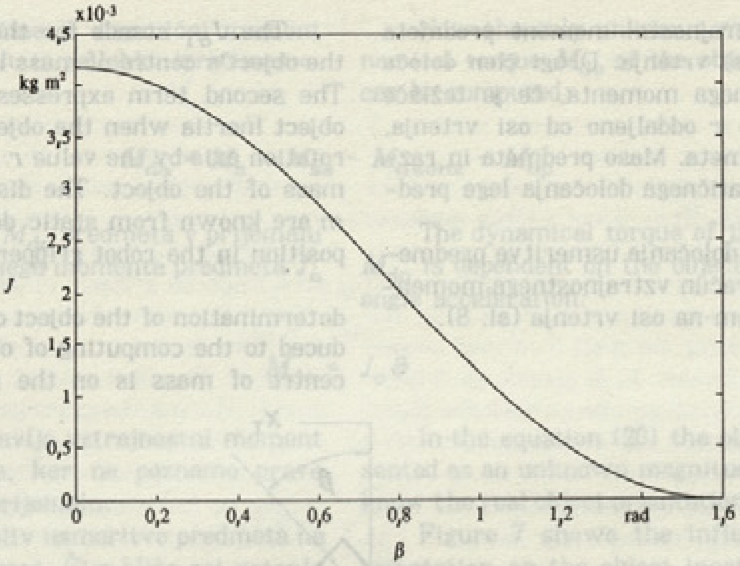
Geometrična oblika predmeta je znana. Z numeričnimi metodami izračunamo vztrajnostne momente v odvisnosti od kota β. Iz primerjave vrednosti J_{oT} določimo usmeritev predmeta β.

We know the geometry of the object. By the numerical methods we can compute the object inertia, according to its dependency upon the object orientation β. By comparison between the values and the measured object inertia J_{oT} the object orientation β can be determined.



Sl. 9. *Kvader: J(β).*

Fig. 9. *An iron block: J(β).*



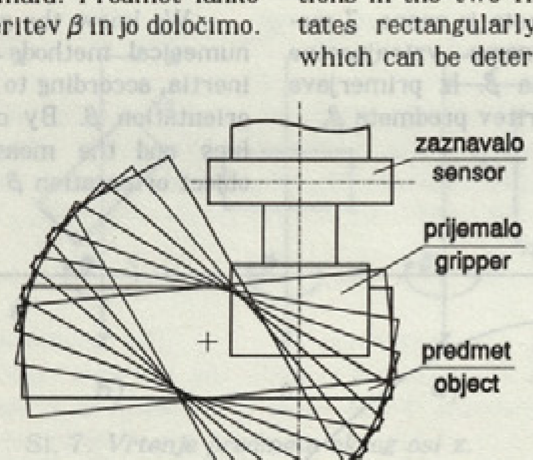
Sl. 10. *Palica: J(β).*
Fig. 10. *An iron stick: J(β).*

Na slikah 9 in 10 vidimo diagrama odvisnosti vztrajnostnega momenta od kota usmeritve β (0 do $\pi/2$). Slika 9 velja za železen kvader $((0{,}12 \times 0{,}06 \times 0{,}03)\ m^3)$, slika 10 pa za železno palico $((0{,}20 \times 0{,}01 \times 0{,}01)\ m^3)$. Diagrama kažeta sinusni odvisnosti $J(\beta)$ obeh predmetov.

Slika 11 prikazuje različne mogoče usmeritve predmeta v dvoprstnem prijemalu. Predmet lahko zavrtimo pravokotno na usmeritev β in jo določimo.

The figures 9 and 10 show the dependence of the object inertia upon the orientation angle β (0 to $\pi/2$). Figure 9 is valid for an iron block $((0.12 \times 0.06 \times 0.03)\ m^3)$. Figure 10 is valid for an iron stick $((0.20 \times 0.01 \times 0.01)\ m^3)$. We can see the sine dependence $J(\beta)$ for the chosen two objects.

Figure 11 shows some possible object orientations in the two fingered gripper. The object rotates rectangularly to the orientation angle β, which can be determined.



Sl. 11. *Različne usmeritve predmeta v dvoprstnem prijemalu.*
Fig. 11. *Possible object orientations in the two fingered gripper.*

4. SKLEP

An, Atkenson in Hollerbach [3] so podobno, zaradi preverjanja, merili lego težišča in vztrajnostni moment bremena v prijemalu robota in dobili rezultate, boljše od 1 odstotka. S tem so upoštevali breme v adaptivni regulaciji robota.

4. CONCLUSION

An, Atkenson and Hollerbach [3] similarly measured the centre of mass position and the object inertia in the robot gripper in control purposes and obtained the results with an accuracy better than 1 %. In this way they considered the load in the adaptive robot control.

Pričakovana točnost določanja lege in usmeritve predmeta v prijemalu je odvisna predvsem od točnosti zaznavala sil in momentov ter od točnosti merjenja kotnega pospeška v trenutku dinamične meritve. Na tržišču je moč kupiti piezoelektrična zaznavala sil in momentov [6, 7], ki imajo zelo dobro dinamiko in pokrivajo zelo široka merilna območja: za sile od nič do 10^6N in za momente od nič do 200 Nm. Pri tem pa dosegajo ločljivost 1 mN do 10 mN oziroma 0,1 mN m. Te podatke primerjajmo z rezultati izračunov (sl. 4, 6) za predmet s težo T = 10 N in ročico, dolgo 0,1 m. Če lego predmeta v prijemalu spreminjamo v mejah od nič do 50 mm, se to kaže v spremembah momenta od nič do 0,5 Nm oziroma 1 Nm pri zavrtitvi za 90^0. Ločljivost zaznavaia na teh merilnih območjih omogoča razlikovanje 5 000 do 10 000 nivojev vrtilnega momenta. To pa v zgornjem primeru pomeni merjenje lege predmeta z ločljivostjo 0,01 mm oziroma merjenje kota φ z ločljivostjo $0{,}009^{\circ}$. Če je absolutni pogrešek zaznavala enak resoluciji zaznavala, je relativni pogrešek oziroma točnost zaznavala 0,05 odstotkov. To so teoretične vrednosti, ki so dosegljive.

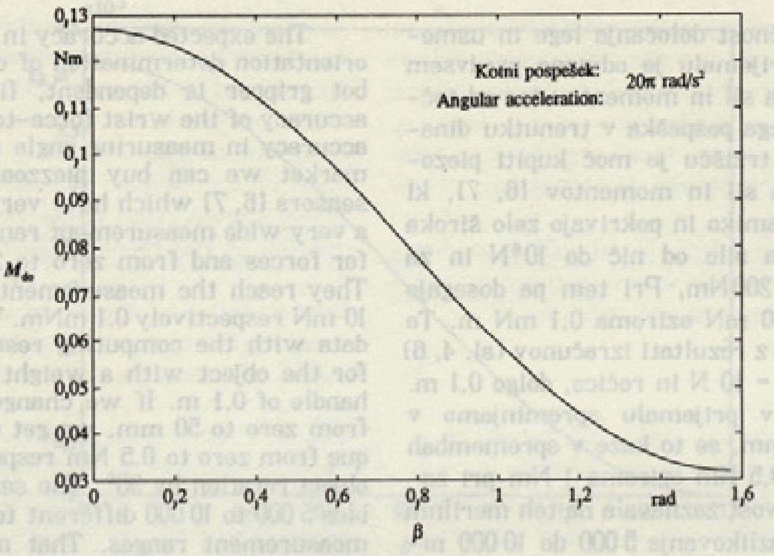
Več težav imamo pri merjenju usmeritve z zaznavalom momentov, ker moramo sinhrono z meritvijo momenta meriti tudi kotni pospešek ali pojemek. Kotni pospešek se pojavi pri vrtenju prijemala le prehodno, zato mora imeti zaznavalo momentov tudi zadostno dinamiko. Najugodnejši trenutek za merjenje je pri največjem kotnem pospešku, zaradi katerega je tudi dinamični moment največji in izkoristek zaznavala boljši. Oglejmo si merjenje usmeritve železnega kvadra. Slika 9 prikazuje odvisnost $J(\beta)$. V primeru, da je največja kotna hitrost prijemala 2π rad/s in pri tem pospeševanje traja 100 ms, bo srednja vrednost kotnega pospeška 20π rad/s^2. Če pospeševanje traja 20 ms, bo srednja vrednost kotnega pospeška 100π rad/s^2. V obeh primerih uporabimo izraz (20) in izračunamo ustrezne dinamične momente M_{do} v odvisnosti od kota usmeritve β (sl. 12, 13).

Usmeritev kvadra se spreminja v mejah od nič do 90^0. Pri tem se dinamični moment spreminja v območju od 0,127 N m do 0,0318 N m (sl. 12) oziroma od 0,6352 N m do 0,1588 N m (sl. 13). Glede na ločljivost zaznavala momentov 0,1 mN m lahko v prvem primeru razpoznamo 952 nivojev vrtilnega momenta, v drugem pa 4 763. To prenesemo na usmeritev in dobimo v prvem primeru ločljivost $0{,}0945^{\circ}$ in v drugem primeru ločljivost $0{,}0189^{\circ}$. Na točnost meritve vplivata še točnost merjenja kotnega pospeška in točnost izračuna $J(\beta)$. Vse tri vplive moramo sešteti in v primeru, ko vsota ne preseže 1%, to pomeni ločljivost vsaj $0{,}9^{\circ}$.

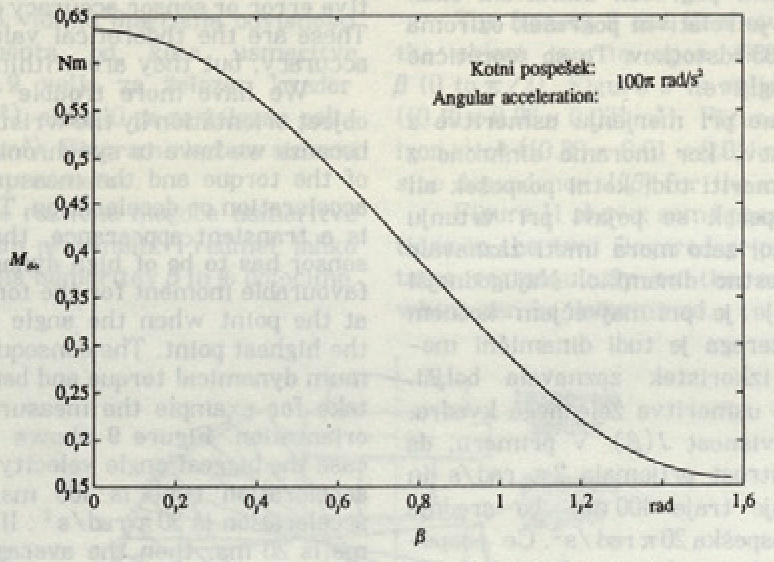
The expected accuracy in the position and the orientation determination of our object in the robot gripper is dependent, first of all, on the accuracy of the wrist force-torque sensor and the accuracy in measuring angle acceleration. On the market we can buy piezzoelectric force-torque sensors [6, 7] which have very high dynamics and a very wide measurement range from zero to 10^6N for forces and from zero to 200 Nm for torques. They reach the measurement resolution 1 mN to 10 mN respectively 0.1 mNm. We can compare this data with the computing results (fig's. 4 and 6) for the object with a weight of 10 N and with a handle of 0.1 m. If we change the object position from zero to 50 mm, we get a change in the torque from zero to 0.5 Nm respectively 1 Nm at the object rotation by 90°. The sensor resolution enables 5 000 to 10 000 different torque levels at these measurement ranges. That means for the upper case the measurement of the object position at the resolution 0.01 mm or the measurement of the angle φ at the resolution of 0.009°. If an absolute error equals the sensor resolution we get a relative error or sensor accuracy equal to 0.05 percent. These are the theoretical values of measurement accuracy, but they are within reach.

We have more trouble with measuring the object orientation by the wrist force-torque sensor because we have to synchronise the measurement of the torque and the measurement of the angle acceleration or deceleration. The angle acceleration is a transient appearance, that's why the wrist sensor has to be of high dynamic value. The most favourable moment for the torque measurement is at the point when the angle acceleration reaches the highest point. The consequences are the maximum dynamical torque and better accuracy. Let us take for example the measurement of iron block orientation. Figure 9 shows dependency $J(\beta)$. In case the biggest angle velocity is 2π rad/s and the acceleration time is 100 ms, the average angle acceleration is 20π rad/s^2. If the acceleration time is 20 ms, then the average angle acceleration is 100π rad/s^2. In both cases we use the equation (20) and compute the corresponding dynamical torques M_{do} dependent of the orientation angle β (fig's. 12 and 13).

We change the iron block orientation in ranges from zero to 90°. In this case, the dynamical torque changes its values from 0.1270 Nm to 0.0318 Nm (fig. 12) or from 0.6352 Nm to 0.1588 Nm (fig. 13). We take the wrist sensor with the torque resolution 0.1 mNm and so we get 952 torque levels for the angle acceleration 20π rad/s^2 (12) and 4 763 torque levels for the angle acceleration 100π rad/s^2 (13). Then we compute the object orientation and get in the first case the angle resolution of 0.0945° and in the second case the angle resolution of 0.0189°. We have another two factors that influence the measurement accuracy. These are the measurement of the angle acceleration and the accuracy of computing $J(\beta)$. We have to take all three influences into account. If the sum does not exceed 1 %, the resolution is 0.9°.



Sl. 12. *Dinamični moment kvadra* M_{do} (β).
Fig. 12. *The dynamical torque* M_{do} (β) *of the iron block.*



Sl. 13. *Dinamični moment kvadra* M_{do} (β).
Fig. 13. *The dynamical torque* M_{do} (β) *of the iron block.*

Tudi če bi pri merjenju lege v praksi dosegli točnost 1 %, to pomeni pri 50 mm ločljivost 0,5 mm ali pri 90^0 ločljivost $0,9^0$.

Zavedati se moramo, da na točnost merjenja vplivajo tudi tresljaji robota, ki delujejo na okrov zaznavala sil momentov ter na prijemalo robota z nezaželenimi pospeški. To se kaže v rezultatih kot naključni šum in bistveno zmanjša teoretično točnost zaznavala oziroma njegovo občutljivost. Majhne spremembe sil in momentov se lahko popolnoma izgubijo v šumu.

Zgornji rezultati že obetajo praktično uporabo v montažni industriji, predvsem pri montaži večjih oziroma težjih predmetov. Robot lahko naključno prijema znane predmete in jih odloži ali vgradi na

Although in practice we gain the position measurement accuracy of 1 % at the range of 50 mm, the resolution will still be 0.5 mm or 0.9^0 at the range of 90^0.

We have to be aware of the fact that the measurement accuracy is dependent on the robot vibrations which influence the wrist sensor casing and the robot gripper by undesired accelerations. Thus we get a noisy result which decreases the wrist sensor accuracy respectively the resolution. Slight changes of forces and torques can be completely wasted in noise.

The upper results promise practical usage in the assembling industry; first of all in assembling big or heavy objects. A robot can coincidentally določeno mesto, npr.: pobira predmete, ki se ustavljajo ob ograji tekočega traku, določa optimalen prijem predmeta in ga ustrezno preprime. Pri znani usmeritvi in legi predmeta v prijemalu lahko ugotavljamo, ali ima predmet ustrezno maso in vztrajnostni moment, kar pomeni, da je z njim vse v redu.

Menim, da lahko zaznavalo sil in momentov v robotiki koristno uporabimo v različne namene. Z vsakim novim opravilom, ki ga bo robot lahko opravil, bo njegova uporabna vrednost večja.

grasp objects known to it and put or assemble them to the desired place. For example: a robot grasps an object which stops at the fence of the conveyor belt, computes the optimum grip and correspondingly grasps the object in a better way. If we know the object position and orientation in the robot gripper then we can find out if the object has the correct mass and inertia, i.e. everything is all right with the object.

In my opinion the wrist force-torque sensor can be used in robotics for many various purposes. The robot' s applicable value will be higher with any new function.

ZAHVALA

Raziskovalno delo je finančno omogočilo Ministrstvo za znanost in tehnologijo Republike Slovenije.

Zahvaljujem se mentorju prof. dr. Alojzu Kralju in prof. dr. Tadeju Bajdu za pomoč in nasvete.

ACKNOWLEDGEMENT

This work was enabled by The Ministry for Science and Technology of the Republic of Slovenia.

I thank my mentor prof.dr. Alojz Kralj and also prof. dr. Tadej Bajd for their kind help and advice.

5. LITERATURA
5. REFERENCES

[1] Tsujimura, T.-Yabuta, T.: Object Detection by Tactile Sensing Method Employing Force/Torque Information. IEEE Transactions on Robotics and Automation. Vol 5, No. 4, 1989, str. 444-450.

[2] Bajd, T.-Kralj, A.: Robotika. Fakulteta za elektrotehniko in računalništvo, Ljubljana, 1991, str. 152-155.

[3] An, Ch.H.-Atkenson, Ch.G.-Hollerbach, J.M.: Model-Based Control of a Robot Manipulator. The MIT Press, Cambridge, Massachusetts, 1988.

[4] Lee, J.: Apply Force/Torque Sensors to Robotic Applications. Robotics 3. North-Holland, 1987, str. 189-194.

[5] Hemami, H.-Goddard, E.: Recognition of Geometrical Shape by a Robotic Probe. Journal of Robotic Systems, Vol. 4, No.2, New York, 1987, 237-257.

[6] Kistler Instrumente AG, Schweiz: Messen mit Kristallen, 1991.

[7] Kistler Instrumente AG, Schweiz: Forschen, Entwickeln, Überwachen durch Kraftmessung, 1991.

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Prejeto: 18.10.1991
Received:

Recenzirano: 20.5.1992
Reviewed: