Strojniški vestnik - Journal of Mechanical Engineering 51(2005)11, 724-736
UDK - UDC 007.52:658.52.011.56
Strokovni članek - Speciality paper (1.04)

Vodenje robota na temelju zaznaval sile in računalniškega vida

Robot Control Based on Force and Vision Sensors

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V prispevku je predstavljen postopek za sledenje krivulji. Med sledenjem robot vzdržuje stik s podlago z zahtevano silo. Metoda temelji na zbiranju in analizi vidne informacije ter merjenju sil z ustreznimi zaznavali. Tako pridobljeni podatki se vključijo v algoritem, tako da se zagotovi želeno delovanje sistema. S postopkom je mogoče izboljšati robotske sisteme v industrijskem okolju.

(Ključne besede: sistemi robotski, vodenje robotov, zaznavalne sile, vid računalniški)

In this paper a robot-control algorithm for tracking a curve on a surface is presented. During the tracking the robot maintains contact with the surface at a predefined force. The method is based on visual information provided by a camera mounted on the robot's end effector, and the measured force acquired from a force sensor. The obtained data are analyzed and the required information is employed in the control algorithm to ensure satisfactory operation. The proposed solution gives new enhancement opportunities for industrial robot-based applications.

(Keywords: robotic systems, robotic control, force sensors, computer vision systems)

0 UVOD

V industrijskih uporabah robotskih sistemov se pogosto pojavi zahteva, da je orodje nameščeno na robotsko roko, v stiku s podlago in sledi določeni krivulji. Primeri take uporabe so nanos lepil ali tesnilnih mas na spojne krivulje površin, poliranje posameznih delov površin ali brušenje spojev med površinami in podobno. Hkrati s sledenjem neki krivulji po površini je v nekaterih primerih uporabe pomembno tudi razpoznavanje same površine po krivulji. Tako je v primerih uporabe mogoče med samim opravilom odkriti različne napake v obliki površin, ki so lahko posledica napake v izdelavi posameznih izdelkov ali vgrajenih komponent v izdelke.

V preteklosti so se mnogi avtorji ukvarjali z opisano tematiko in so se problemom posvečali na različne načine. V prvih fazah poskusov vodenja robotov z optičnimi zaznavali so bili ti v večini primerov zasnovani na kalibriranih sistemih, ki so delovali na temelju izgradnje 3D informacije iz stereo ali podobnih sistemov za zajem slik, kjer so bile kamere za zajem večinoma nepremično nameščene, ali vodene

0 INTRODUCTION

In industrial applications there are frequent demands to maintain contact between the tool mounted on the robotic hand and the processed surface. Examples of such demands are the operations where a glue or a sealant needs to be carried to the surface, where the polishing of a surface has to be performed or where a contact between surfaces has to be brushed. For such robotic applications it is also interesting to be able to detect surface defects, or to identify the wrong types of assembled parts. This can be solved by identifying the shape of the surface along the tracked curve.

In the past, several researchers have worked in this field. The first tests of robot control with visual sensors were based on calibrated systems. 3D information about the environment was acquired by stereo or similar visual systems. Cameras were fixed or controlled by special camera-control manipulators. Such systems have some drawbacks that limits their practical use, e.g., high calculation demands and the occlusions of observed scenes in the case of fixed s posebnimi rokami za vodenje kamer. Stereo sistem ima velike računske zahteve, poleg tega pa se posebej v primeru stalno nameščenih kamer pojavijo problemi zakrivanja opazovanih predmetov. Za zmanjšanje računske zahtevnosti so bile opravljene določene poenostavitve na podlagi analize stereo slik med približevanjem robotske roke predmetu. V zadnjih letih so se na področju robotike in vgradnje robotskega vida v sisteme pojavili sistemi z vizualnim zaznavalom, nameščenim na vrh robotske roke. S to postavitvijo se je mogoče izogniti problemu zakrivanja, poveča pa se natančnost zaradi ožjega področja zanimanja [1]. Problem robotskih sistemov, opremljenih zgolj z vizualnimi zaznavali, so optične lastnosti, ki jih morajo za robustno delovanje 3D algoritmov vsebovati opazovani predmeti. Z namenom,da se zagotovi stalen stik s podlago in hkrati omogoči sledenje potem po površinah, so se razvili sistemi, ki vsebujejo kombinacijo vizualnih zaznaval in zaznaval sile, ki merijo silo, s katero robotska roka pritiska na površino. Zaznavalo sile je lahko nameščeno različno. Namestitev zaznavala sile na vrhu orodja se uporablja predvsem za natančno sledenje obrisov [2], vendar taka razporedba onemogoči namestitev orodja, zato se pogosteje gradijo sisteme z zaznavalom sile v zapestju robota.

Kombinacije teh zaznaval je za sledenje krivulji na neznani podlagi z nespremenljivo silo v smeri orodja uporabil Xiao [3]. Opisani način ne omogoča določitve nagiba površine. Sistem poišče točke na ravnini in predpostavi, da je krivulja med sosednjima točkama premica. Kamero, nameščeno na vrh robota, sta uporabila Baeten ([4] in [5]) za predikcijsko sledenje obrisa ravnega predmeta in Malis [6] pri natančni namestitvi orodja. Vsi navedeni primeri vsebujejo zgolj eno s silo vodeno smer, tako da ne pridobijo informacije o usmeritvi orodja na podlago.

V prispevku je opisana metoda, ki omogoča sledenje krivulji in zaznavanje usmeritve in temelji na hitrostno vodenem robotu. Sistem poskrbi za sledenje krivulji, zarisani na površini, tako da vrh orodja, nameščenega na robotski roki, zagotavlja stalen stik s površino, ne glede na njeno obliko. Sistem na vsaki točki poti določi normalo na površino in razpozna točko površine glede na celotni koordinatni sistem.

Sistem je zasnovan na zaznavalu sile in podaja informacijo o silah, ki delujejo na orodje v trirazse□nem prostoru in na slikovnem zaznavalu, ki preslika 3D informacije v dvorazsežni slikovni

cameras. To reduce the calculation demands some simplifications based on image analyses were introduced during the approach to the observed objects. In recent years robotic systems with the image sensor mounted on the end effector appeared. With this configuration the problems of occlusion can be avoided and a higher accuracy, because of a more focused area of interest, can be achieved [1]. The main problem of robotic systems based only on visual sensors are the optical characteristics of the observed objects required in order to achieve robust behavior of the 3D extraction algorithms. To establish and maintain a constant contact with the surface and simultaneously to track the desired trajectory, systems consisting of visual and force sensors were developed. Force sensors can be mounted in various ways. If the sensor is attached to the top of the tool the system is able to attain precise contour tracking [2]. Such a configuration disables the installation of a tool, therefore wrist-mounted force sensors are used in many cases.

The combination of the described sensors for curve tracking on an unknown surface with constant force in the direction of the tool was presented by Xiao [3]. With this approach it was not possible to identify the surface orientation. In the experiment some simplifications were made, and then the system was only capable of moving from the starting point to the end point in a straight line. A camera mounted on the top of the manipulator was used by Beaten ([4] and [5]) for predictive, planar contour tracking and by Malis [6] for the precise placement of the tool. In all these examples the force was controlled in only one direction. Consequently, no information about the orientation between the tool and the surface can be derived, and hence no identification of the surface orientation can be made.

With the method presented in this paper, a velocity-controlled manipulator tracks a curve drawn on an uncalibrated surface and perceives its orientation. The system maintains constant contact with the surface and tracks the curve regardless of the dynamics of the surface or the curve. With the proposed method, in each position of the curve the surface normal is determined and the tool is placed perpendicular to the surface.

Our system consists of a force sensor and a vision system. The force sensor provides six dimensional information about the force and torque acting on the tool, while the camera transforms 3D prostor. Slikovno zaznavalo je v našem primeru nameščeno na zapestje robotske roke, kar preprečuje zakrivanje, hkrati pa ni ovira za izbiro ustreznega orodja. V nadaljevanju prispevka je opisana metoda zbiranja informacije o silah in slikovne informacije, postopek združitve informacij, pridobljenih iz obeh zaznaval, delovni prostor robota. Nazadnje je opisana uporaba modela hibridnega vodenja. Sistem je bil v praksi zgrajen iz gradnikov, ki so opisani v poglavju Eksperimentalni sistem. Prispevek se konča s sklepnim poglavjem, v katerem so opisane naše ugotovitve in podane možnosti izboljšave sistema.

1 METODE IN POSTOPKI

Namen našega sistema je sledenje krivuljam na neznani površini in ob tem ohranjati orodje, usmerjeno pravokotno na podlago. Zadano nalogo je mogoče izvesti s kombinacijo zaznaval različnih veličin. Sledenje krivulji je izvedeno z računalniškim vidom, medtem ko se orodje površini prilagaja na podlagi informacij, pridobljenih iz zaznavala sile. Združevanje različnih informacij, pridobljenih iz zaznaval, ki obsegajo različne veličine in so ob tem še prostorsko odmaknjeni, je treba predstaviti kot celoto in jo uporabiti za učinkovito vodenje robota. Združitev podatkov, zbranih z merilnikom dotika in slikovnim zaznavalom, je zaradi njegovih lastnosti primerno izvajati v delovnem prostoru. Ta prostor omogoča preslikavo sil in leg sledene krivulje, zajete s slikovnim zaznavalom, v različne koordinatne sisteme. S tem opisom okolja se vzpostavi pravokotnost, ki omogoča neodvisno, hibridno vodenje na podlagi slikovne informacije in meritve sil.

1.1 Delovni prostor

Povezavo med silami in lego v delovnem prostoru je prvi definiral Mason [7]. Delovni prostor je postavljen v delovno točko orodja. Vse naloge v delovnem kartezičnem koordinatnem sistemu (KS) se razstavijo na tri premike v smereh x, y, z in tri zavrtitve okrog osi x, y, z. S kombinacijo izvajanja teh podnalog se izvedejo zelo raznolike robotske naloge.

Predstavitev delovnega prostora omogoča tudi preslikavo sil in vrtilnih navorov iz zaznaval v delovni prostor. Z uporabo predstavitve usmeritve z vzponom, odklonom in nagibom (VON - RPY), ki je najpogosteje uporabljena pri vodenju robotov, se

information of the scene into the image space. The camera mounted on the hand of the robotic manipulator reduces the possibility of occlusion and also gives the opportunity to use a fastened-on end-effector. In this paper the method of the force and vision sensors data acquisition and data analysis is described. The extracted data are integrated into a proposed task frame. The proposed method was validated by different tests that were carried out on a testbed described in the section called Experimental system. In the Conclusion the findings and some challenging future improvements of our system are discussed.

1 METHODS

The main goal of our work is to track a curve on an unknown surface. Additionally, the tool has to be oriented perpendicular to the surface. The given task can be executed using the data obtained by sensors of different modalities. The curve tracking is based on a vision system, while the tool adaptation to the surface is controlled by a force sensor. Sensor information, which represents the different modalities and is retrieved in different positions, has to be combined in its entirety to be used for efficient robot control. The integration of the data captured by the force and the vision sensors is reasonable to be done in the task frame. The task frame formalism enables the transformation of forces and the position of the tracked curve captured by the vision sensor, between different coordinate systems (CSs). Within the task frame the orthogonality is established. This enables hybrid control based on visual information and force measurement.

1.1 Task frame

The linkage between the force and the position in the task frame was proposed by Mason [7]. The task frame is positioned on the top of the tool. All tasks in the task frame's Cartesian coordinate system (CS) are divided into three translations in the direction of the coordinate axes and the three rotations around the coordinate axes. Through a combination of the defined basic motions all the robotic tasks can be executed.

In the task frame formalism the forces and torques can be transformed from one coordinate system (CS) to another. If the orientation is represented as roll, pitch, yaw (RPY) (which is most commonly used in manipulator control) then the sile (*F*) in vrtilni navori (*τ*) na posamezne koordinatne sisteme preslikajo takole:

forces and torques between different CSs are transformed in the following way:

$$ {}_{t}\vec{F} = \mathrm{RPY}({}_{s}^{t}\varphi_{x}, {}_{s}^{t}\varphi_{y}, {}_{s}^{t}\varphi_{z})\, {}_{s}\vec{F} \quad (1), $$

$$ {}_{t}\vec{\tau} = \mathrm{RPY}({}_{s}^{t}\varphi_{x}, {}_{s}^{t}\varphi_{y}, {}_{s}^{t}\varphi_{z})\ \left(({}_{s}^{t}p_{x}, {}_{s}^{t}p_{y}, {}_{s}^{t}p_{z})^{T} \times {}_{s}\vec{F} + {}_{s}\vec{\tau}\right) \quad (2), $$

kjer oznaka $^{(.)}$ označuje KS, iz katerega poteka preslikava, $_{(.)}$ pa KS, v katerega se sile prenesejo.

V našem delu opazujemo štiri KS. Prvi je pritrjen na vrh orodja in ga označimo s predpono $_{t}(.)$, drugi predstavlja kamero $_{c}(.)$, tretjega pa določa zaznavalo sile $_{s}(.)$. Vse dogajanje je predstavljeno v osnovnem KS robota. KS orodja in merilnika sil in vrtilnih navorov sta enako usmerjena in premaknjena v smeri osi *z* za razdaljo *L*. Razdalja *L* je zaradi podajnega orodja odvisna od sile, ki deluje v smeri orodja in jo določimo posredno prek $_{s}F_{z}$:

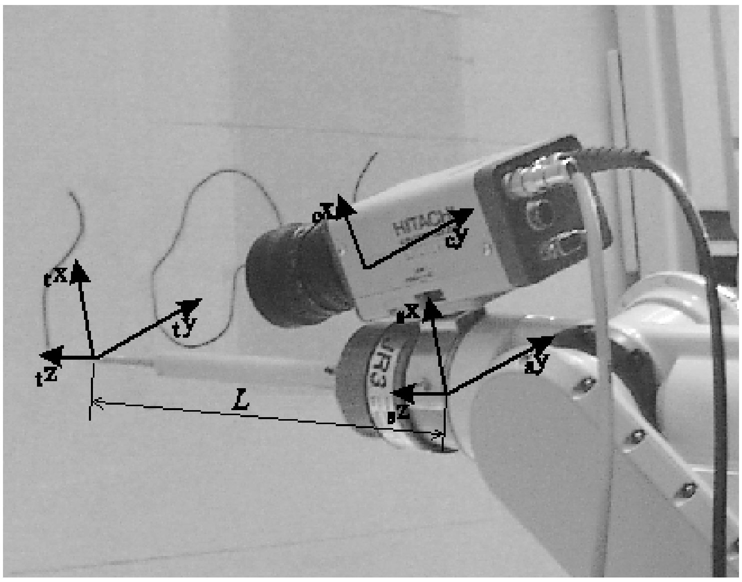
where $^{(.)}$ marks the CS from which the data is processed, while $_{(.)}$ represents the destination CS.

In our work four CSs are observed. The first one $_{t}(.)$is attached to the top of the tool, the second one $_{c}(.)$ represents the vision sensor, the third one $_{s}(.)$ defines the CS of the force sensor. All the occurrences are presented in base CS of the manipulator. The CS of the tool and the CS of the force sensor have the same orientation and are translated for *L* in the *z* direction. Because of the compliant tool the distance *L* is subjected to the contact force *F* hence, the force *L* is measured indirectly through force $_{s}F_{z}$:

$$ L = L_0 + \mu\, {}_{s}F_{z} \quad (3), $$

kjer sta L_0 razdalja med izhodiščema $_{t}$KS in $_{s}$KS, ko na orodje ne deluje nobena sila dotika, μ pa koeficient podajnosti orodja. Medtem ko so medsebojne usmeritve med $_{t}$KS, $_{s}$KS in $_{c}$KS stalne, pa se njihova lega glede na osnovni KS spreminja. Preslikavo med KS zaznaval in baričnim KS določimo na podlagi kinematike robota.

where L_0 is the distance between $_{t}$CS and $_{s}$CS, when there is no contact force on the tool, and μ is the coefficient of the tool compliance. The orientations between $_{t}$CS, $_{c}$CS and $_{s}$CS are fixed. However, their position in the base CS is changing. The transformation between these CSs and the base CS is obtained from the direct kinematics of the robot.



Sl. 1. *Postavitev koordinatnih sistemov*
Fig. 1. *Placement of coordinate systems*

1.2 Merilnik sile in vrtilnega navora

Merilnik sile in vrtilnega navora je nameščen v zapestju robota in izveden tako, da kot rezultat vrača izmerjene vrednosti sil in vrtilnih navorov v smereh pravokotnih osi x, y, z. Izmerjena sila $\vec{F}_r$ je sestavljena iz sil dotika $\vec{F}_{co}$, pospeška robota $\vec{F}_a$ in težnosti $\vec{F}_g$:

1.2 Force sensor

The force sensor is mounted on the wrist of the manipulator. We measure the forces and torques in the orthogonal directions x, y, z. The measured forces consist of the contact $\vec{F}_{co}$, inertia $\vec{F}_a$ and gravity $\vec{F}_g$ forces:

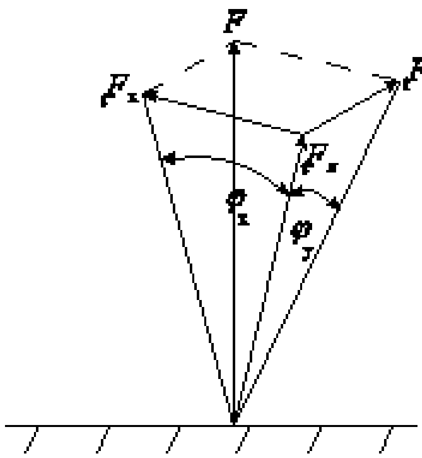
$$\vec{F}_r = \vec{F}_{co} + \vec{F}_a + \vec{F}_g \quad (4).$$

Za namen vodenja je pomembna samo informacija o sili stika, zato je treba iz meritev odstraniti vpliv teže in vztrajnosti. Za izravnavo vztrajnosti je treba poznati pospeške orodja. V večini primerov pospeškov ni mogoče meriti. Ker so pospeški majhni v primerjavi s silami, s katerimi delujemo na obdelovano površino, lahko $\vec{F}_a$ v našem primeru zanemarimo. Vpliv teže orodja izravnamo v fazi kalibracije robotskega sistema na način kakor ga je predlagal Omrčen [8]. Pri tem postopku na podlagi meritev sil in vrtilnih navorov v treh različnih znanih usmeritvah izračunamo maso in težišče orodja. Usmeritev orodja pridobimo v vsaki točki iz zavrtitvene matrike robota. Iz tako pridobljenih podatkov izračunamo $\vec{F}_g$ in jo odštejemo od izmerjene $\vec{F}_r$. Sile, zaznane z zaznavalom sile, se z enačbama (1) in (2) preslikajo na vrh orodja. V nadaljevanju se oznaka F zaradi poenostavitve zapisa nanaša le na sile, ki se vzpostavijo zaradi stika orodja s podlago.

Tako obdelani podatki so uporabljeni za identifikacijo površine. V statičnih razmerah sila podlage deluje na orodje v smeri normale na podlago.

In the control we need only the information about the contact. Therefore, we have to eliminate the contribution of the gravity and the inertia forces from the measured data. If the exact acceleration of the tool were to be known, inertia could be compensated. However, in our case $\vec{F}_a$ is small compared to $\vec{F}_{co}$ and therefore, it can be neglected, i.e., the gravity influence was compensated in the calibration phase of the robotic system as proposed by Omrčen [6]. On the basis of force and torque measurements in three known different orientations of the tool weight and the centre of mass of the tool can be calculated. The orientation of the tool is known in each point (from the rotation matrix of the robot). $\vec{F}_g$ can be calculated and subtracted from the measured $\vec{F}_r$. Using Equations (1) and (2) the forces measured with the force sensor are transformed to the top of the tool. For simplicity we denote in the following the contact forces between the tool and the surface as F.

The processed data are used for the surface identification. In static conditions the force of the surface acts on the tool in the direction normal to the surface.



Sl. 2. *Sila dotika, delujoča na vrh orodja*
Fig. 2. *Contact force on the top of the tool*

Iz komponent sile F izračunamo nagibna kota glede na površino (sl. 2):

From the components of force F the inclination angles to the surface are calculated (Fig. 2):

$$\varphi_x = \arctan(\frac{F_x}{F_z}) \quad (5)$$

$$\varphi_y = \arctan(\frac{F_y}{F_z}) \quad (6).$$

Kadar tipalo drsi po površini, se v sili F izmeri tudi sila trenja, ki deluje v nasprotni smeri gibanja. Silo trenja je mogoče oceniti v primeru znanega koeficienta trenja in ravnih površin, kar pa v praksi ni najbolj pogosto. V primeru neupoštevanja sile trenja se pri drsenju pojavi določen kot napake pri nagibu orodja glede na normalo površine. To napako zmanjšamo z uporabo orodij z majhnim koeficientom trenja.

When the tool is sliding over the surface a frictional force in the opposite direction of the motion is present. The friction force can be calculated only if the friction coefficients are known and the surface is flat. As in practice this is usually not the case, the influence of the friction is neglected and consequently some error is introduced to the inclination angles. To minimize these errors we use tools with low friction coefficients.

1.3 Slikovno zaznavalo

Za sledenje na površini izrisane poti uporabimo na zapestje nameščenno slikovno zaznavalo (kamera). Zajeto sliko je treba obdelati. Da bi sistem omogočal kar najbolj robustno delovanje, je zajem slikovne informacije zastavljen na barvni kameri, v barvnem prostoru "barvni odtenek - nasičenost - vrednost" (HSV). Slika je razčlenjena na podlagi barvne sestavine H in S. V prvi fazi se v področju zanimanja, predstavljenem v pravokotniku s polno črto (sl. 3a), na podlagi barvne informacije določi področje slike, ki pripada orodju. Iz tega področja se izračuna koordinate vrha orodja P_t. Zaradi znane medsebojne lege orodja, glede na kamero, se pri analizi slike poišče le vrh podajnega orodja, katerega dolžina se v odvisnosti od sile, s katero deluje na podlago, lahko spreminja. Potek krivulje se poišče s Canny-evim postopkom iskanja robov na sestavini barvnega prostora H (sl. 3b).

Krivulja na sliki ima dva robova. Za točke krivulje so upoštevane zgolj točke srednjih vrednosti robov. Ob tem se preveri še, ali je odtenek barve med robovoma podoben barvi, ki je v fazi kalibracije določena kot barva krivulje. Na podlagi segmentiranih podatkov se po metodi najmanjših kvadratov približa potek krivulje s kvadratnim polinomom v smeri premika orodja (sl. 3c). V višini vrha orodja j se iz približne krivulje določi tangento in izračuna razdaljo med orodjem in tangento e_y (sl. 3d). Po tangenti se določi kot φ_z glede na smer i.

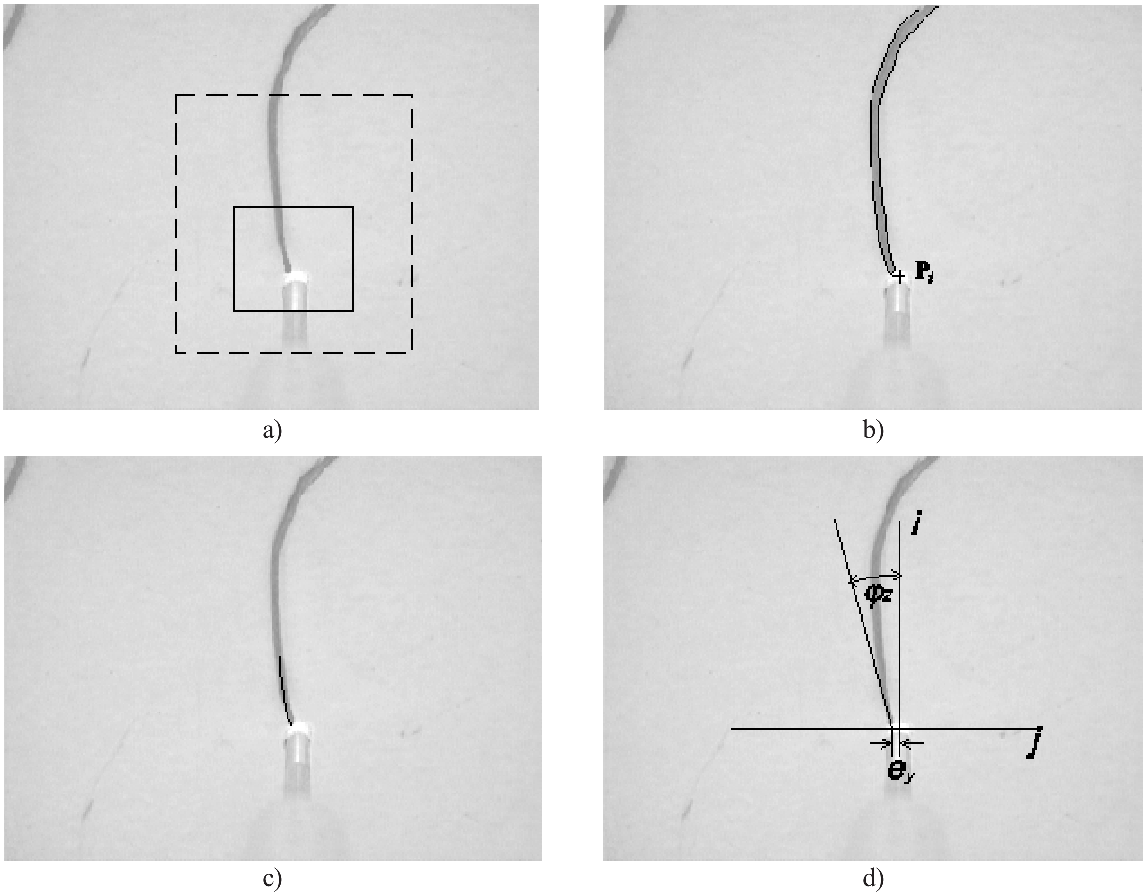
Za boljše spremljanje krivulje upoštevamo še njeno ukrivljenost (B). Ta postopek se izvaja na večji

1.3 Vision sensor

The information acquired from the wrist-mounted visual sensor (camera) is used for tracking the trajectory drawn on the surface. The captured images have to be analyzed. To achieve robust image segmentation a color camera was used. Data was processed in the "Hue-Saturation-Value" (HSV) space. The image was segmented into H and S color components. Based on color information the region of the image that belongs to the tool was identified. These data were used for a calculation of the coordinates of the top of the tool. Because of the known mutual position between the tool and the camera only the position of the top of the tool, which can change according to the compliant tool, has to be found. The curve is searched by the Canny edge detector of the H component in the color space (Fig. 3b). The color of the curve is determined in the calibration phase.

The curve is color coded and has two edges. The points of the curve are calculated as mean values in the region between the two edges. Based on the segmented image data the direction of the curve is approximated with a second-order polynomial calculated by the least-squares method (Fig. 3c). The tangent to the approximated curve at the position where the top of the tool is in contact with the curve gives the direction of the curve. The distance e_y between the tangent and the top of the tool is estimated and the angle φ_z is calculated from the tangent (Fig. 3d).

To define the optimal robot speed in the direction along the curve a bending factor *(B)* of the trajectory is calculated. This procedure is done in a wider region (Fig. 3a dashed rectangle) than the



Sl. 3. *Razgradnja slike: a) manjši pravokotnik pomeni območje za izračun tangente, črtkan pa za oceno ukrivljenosti z Wang-ovim detektorjem; b) določitev vrha orodja in točk krivulje; c) približek krivulje; d) vrednosti za slikovno sledenje*

Fig. 3. *Image segmentation: a) Smaller rectangle represents the region for the calculation of the tangent, the dashed rectangle is used for an estimation of curve bending; b) Determination of the top of the tool and the points of the tracked curve; c) Approximated curve; d) Values for the curve tracking*

dolžini krivulje (sl.3, črtkan pravokotnik), tako pridobimo boljšo informacijo o dinamiki spreminjanja krivulje. Ukrivljenosti krivulje (*B*) smo ocenili z Wang-ovim detektorjem [9].

1.4 Hibridno vodenje

Ker želimo voditi robot po legi in sili, smo uporabili hibridno vodenje, ki ga shematsko ponazarja slika 4. Vhodni primerjalni vrednosti sistema sta želena sila, s katero orodje deluje na površino, in največja hitrost gibanja po krivulji.

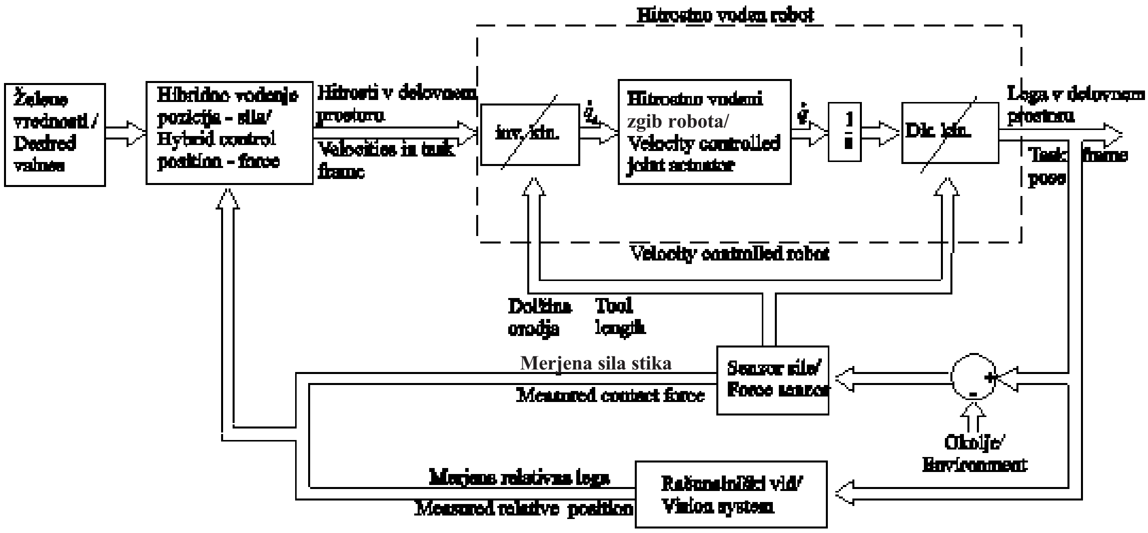
Hibridno vodenje združuje položajno vodenje in vodenje sile, izvedeno kot zunanja krmilna zanka okrog, zgibno krmiljenega, robota. Za preslikavo iz zgibnega prostora v delovni prostor uporabimo

estimation of the tangent and gives more global information about the curve dynamics. The bending factor of the curve is obtained by the Wang detector [9].

1.4 Hybrid control

The robot is based on a hybrid control, as schematically illustrated in Fig. 4. The desired force acting on the surface and the maximum speed along the tracked curve are the reference input values.

The hybrid control structure combines the sensor-based position and the force control, implemented as an outer control loop around the joint controlled robot. For the transformation from the joint space to the task space the robot kinematics



Sl. 4. *Shema hibridnega vodenja okrog hitrostno vodenega robota*
Fig. 4. *Hybrid control scheme around the velocity-controlled robot*

robotsko kinematiko. Po podatku o sili F_z izračunamo dolžino podajnega orodja z enačbo (3). Dolžina orodja vpliva na parametre inverzne in neposredne kinematike. V danem sistemu so smeri vodene s podatki o sili stika in relativne lege orodja. Glede na to, da obravnavamo hitrostno voden sistem, bodo v nadaljevanju podani postopki vodenja izraženi v hitrostnem prostoru.

is used. The length of the compliant tool affects the direct and inverse kinematics and the length of the compliant tool is calculated using the Equation (3). In the presented system all the directions are controlled according to the contact force or the relative position of the tool on the curve. Because the robot is velocity controlled, all the control actions are in the velocity space.

1.5 Vodenje sile

V smereh, vodenih s silo, je poglavitni namen vzdrževati zanesljiv stik orodja s podlago, tako da je sila nespremenjena in leži orodje pravokotno na podlago. Vodenje robota z željeno silo na podlago zagotavljamo s proporcionalnim krmilnikom:

1.5 Force control

In the directions controlled by the force the main goal is to maintain a constant contact with the surface so that the force is constant and the tool is perpendicular to surface. This is ensured by a proportional controller:

$$v_z = k(F_{dz} - F_z) \qquad (7),$$

kjer so v_z zahtevana hitrost, F_{dz} in F_z želena in merjena sila v podani smeri ter k koeficient ojačanja.

Po podatkih o zaznani sili F na podlagi enačb (5) in (6) izračunamo nagibna kota orodja glede na normalo površine. Zaradi zahteve, da je orodje usmerjeno pravokotno na podlago, opravljamo zavrtitev okrog osi ${}_t x$ in ${}_t y$ s proporcionalnim krmiljenjem po enačbah:

where v_z is the control velocity, F_{dz} and F_z are the desired and the measured forces in a given direction, and k is amplifying the gain.

Force information is also used to determine the slant angles between the tool and the normal to the surface (5) and (6). To establish and maintain the orientation of the tool perpendicular to the surface the following angular velocities control is used.

$$\omega_x = -k_\omega \varphi_x \qquad (8)$$

$$\omega_y = -k_\omega \varphi_y \qquad (9).$$

Usmeritev površine se izračuna iz usmeritve orodja in zavrtitvene matrike robota.

Knowing the tool orientation and the robot-orientation matrix means that the orientation of the surface can also be estimated.

1.6 Sledenje krivulji

1.6 Curve tracking

Sledenje krivulji je izvedeno z nekalibrirano kamero, kar pomeni, da vrednosti o absolutni vrednosti razdalj med koordinatnim sistemom kamere in orodja niso podane. Vidno vodenje je razbito na dve pravokotni smeri, kjer se v smeri y popravlja napaka e_y (sl. 3d) lege orodja pravokotno na os ${}_t x$:

The visual control is performed by an uncalibrated camera system. Hence, the absolute relation between the coordinate system of the camera and the top of the tool is not known. The visual tracking is divided into two orthogonal directions, where in the course of ${}_t y$ the error of e_y is corrected (Fig.3d).

$$v_y = -k_y e_y \quad (10).$$

Na osnovi informacije kota med tangento na krivuljo in osjo ${}_t x$ se izvede popravek zasuka orodja okrog osi ${}_t z$:

Based on information about the angle between the tangent on the curve and the axis, the rectification of the orientation of the tool around ${}_t z$ is made:

$$\omega_z = -k_{\omega z} \varphi_z \quad (11).$$

1.7 Hitrostno vodenje

1.7 Velocity control

V primeru, da bi bil opisani sistem namenjen sledenju po nezahtevnih krivuljah in ravnih površinah, bi vodenje robota lahko vedno izvajali s stalno hitrostjo robota v smeri osi ${}_t x$. Glede na to, da je naš cilj vodenje robota tudi po razgibanih površinah in po zelo ukrivljenih krivuljah, zarisanih na površini, je hitrost vodenja robota treba prilagoditi spremembam smeri sledene krivulje in razgibanosti površine. Zmanjševanje hitrosti zaradi ukrivljenosti krivulje je nujno zaradi zahteve po pravokotnosti med zaznanimi smermi v delovnem prostoru, kar zagotovi natančnejše izvajanje sledenja primerjalni krivulji v točkah ukrivljenosti.

Ob drsenju vrha orodja po površini se v primeru pomikov z velikimi hitrostmi ob razgibani površini dogaja, da vrh orodja na površino ne deluje z želeno silo, ali da na površino ni postavljeno popolnoma pravokotno. Da se zagotovi želeno sledenje je v tem primeru treba hitrost robota v smeri osi ${}_t x$ ustrezno zmanjšati.

Hitrostno vodenje robota v smeri pomika orodja je zato izraženo z enačbo

In the case when the proposed system is used for tracking a simple curve and almost flat surfaces robot control along direction ${}_t x$ with constant velocity. Our goal is also to track a curve on a more complex surface and curves with a more dynamic course; therefore, we have to adapt the velocity in a given direction according to the profile of the curve and to the shape of the surface. The bending of the curve could cause that axis ${}_t x$ not to be aligned with the tangent to the curve. In this case the system's ability to track a curve would be compromised.

At high velocity, sliding of the tool on the dynamic surface can occur, so that the top of the tool would not act on the surface with the desired force and the tool is not perpendicular to the surface. To ensure the desired tracking, the velocity ${}_t v_x$ in the direction ${}_t x$ has to be appropriately reduced.

The velocity control in direction ${}_t x$ can be expressed in following way

$$v_x = v_{x\max} - k_F \, \| \vec{F} - \vec{F}_d \| - k_B B \quad (12),$$

kjer je v_{xmax} največja dovoljena hitrost, $\| \vec{F} - \vec{F}_d \|$ je norma razlike med želeno in merjeno silo, B pa koeficient ukrivljenosti krivulje.

where v_{xmax} is the maximum-allowed velocity, ${}_t\vec{F}$ and ${}_t\vec{F}_d$ are the measured and the desired force on the top of the tool and B is the coefficient of curve bending.

Celotno vodenje v prostoru hitrosti zapišemo takole:

Combining all the partial velocity controls we obtain:

$$\begin{bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} v_{x\,max} - k_F \,||\, \vec{F} - \vec{F}_d \,||\, - k_B B \\ -k_y e_y \\ k_z (F_{dz} - F_z) \\ -k_\omega \varphi_x \\ -k_\omega \varphi_y \\ -k_{\omega z} \varphi_z \end{bmatrix} \quad (13).$$

2 PREIZKUSNI MODEL

Sistem sestavlja robot Mitsubishi PA-10 z zaznavalom sile JR3 in kamero Hitachi KP-D50 ločjivosti 640×480 na vrhu robota. Vodenje robota in zbiranje informacij z zaznavala sile poteka s frekvenco 700 Hz, medtem ko zbiranje in obdelava slik poteka s frekvenco 30Hz. Robot je hitrostno voden, kar pomeni, da so vhodi v krmilnik kotne hitrosti v sklepih robota.

2 EXPERIMENTAL MODEL

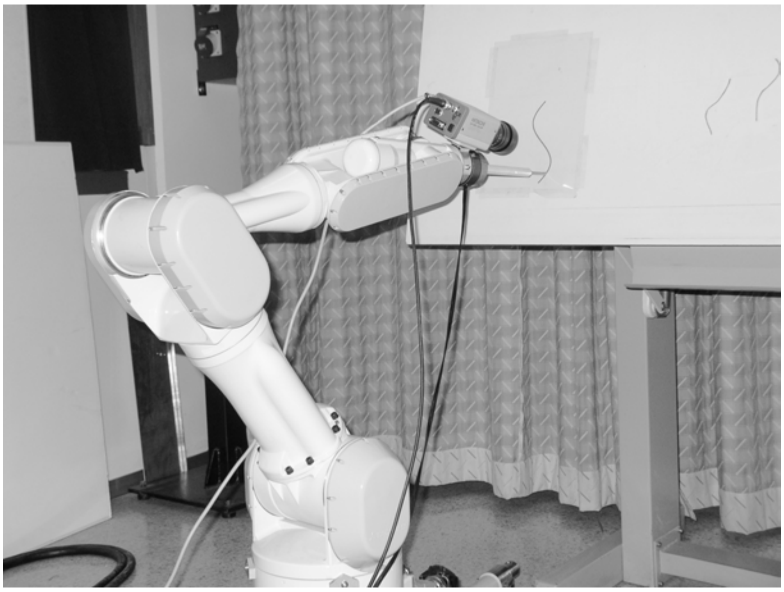
The system combines Mitsubishi Pa-10 robot with the JR3 force sensor and the wrist-mounted Hitachi KP-D50 color camera with a resolution of 640x480. The robot control and the force acquisition work at 700 Hz, meanwhile the camera capturing and the image analysis is maintained at a frequency of 30 Hz. The robot is velocity controlled, so the inputs to the controller are the angular velocities of the robot's joints.

3 PREIZKUSNI REZULTATI

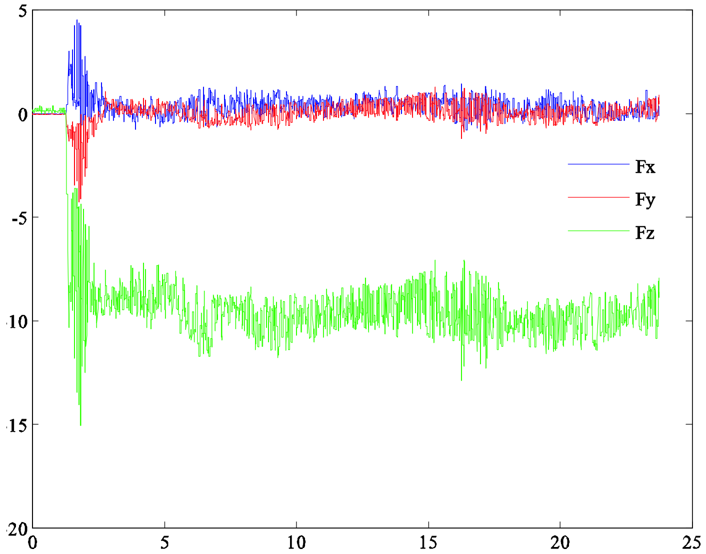
Predlagano metodo smo preizkusili na prej opisanem sistemu. Robot mora slediti krivulji na neznani togi površini. Delovna naloga je podana v delovnem prostoru robota. Znana trajektorija je načrtana na ravni obdelovani površini, po kateri

3 EXPERIMENTAL RESULTS

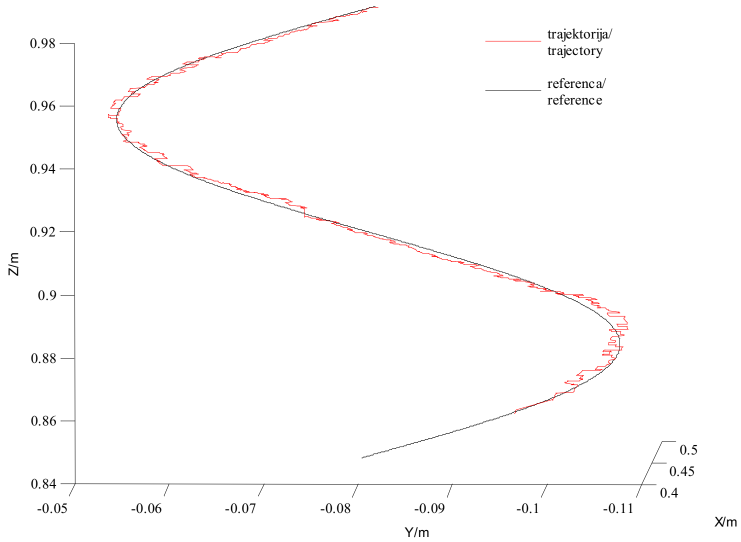
The proposed method was tested on the described system. The robot had to track a curve on an unknown stiff surface. A trajectory with a known shape was drawn on a plain surface. The curve had to be tracked with a maximum velocity of 0.01 ms^{-1}



Sl. 5. *Preizkusni model*
Fig. 5. *Experimental model*



Sl. 6. *Sile na vrhu orodja*
Fig. 6. *Forces on the top of the tool*



Sl. 7. *Dejanska pot vrha robota v referenčnem KS*
Fig. 7. *Actual trajectory of the end effector in the reference CS*

želimo drseti z največjo hitrostjo 0,01 ms^{-1} ob tem pa mora delovati na podlago s silo 10N .

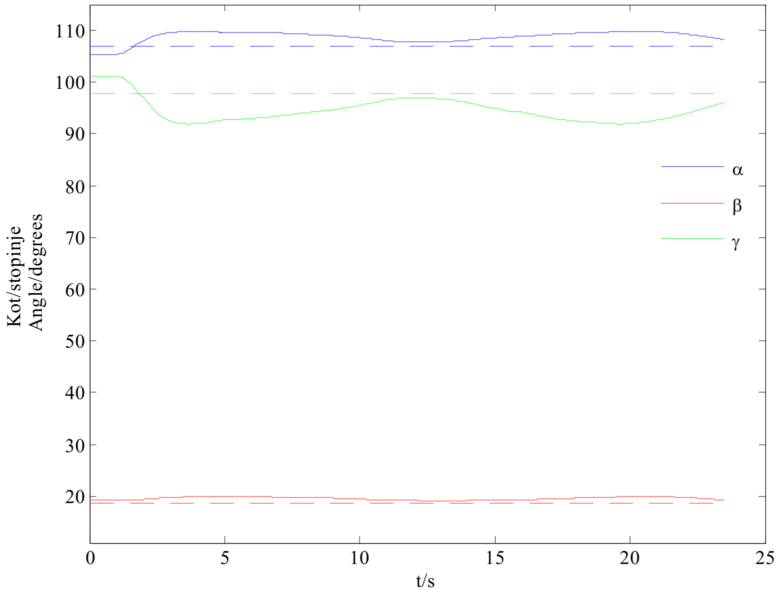
Rezultati preizkusov so predstavljeni na slikah 6 do 8. Merjeni podatki o silah vsebujejo informacijo o dotiku in tudi o vztrajnostnih silah, zato se v fazi vzpostavljanja sile pojavijo nihanja (sl. 6). Sistem po 0,5 s vzpostavi želeno silo pritiska F_z. Sili v preostalih smereh se stabilizirata 2 s.

S slike 7 je razvidno, da je sistem zmožen slediti želeni krivulji, vendar pa zaradi nenatančne informacije o dolžini orodja prihaja do premikov v

and tool had to maintain a constant contact force of 10 N.

The results of the test are presented in Figures 6–8. As the measured data also include information about the inertia forces, some oscillations appear in the transient phase (Fig. 6). The system is able to establish the desired force in the z_t direction in 0.5 s. Forces in other two directions stabilize in 2 s.

From Fig. 7 it is evident that the system is able to track the desired curve. Because of the inaccurate information about the tool length, there



Sl. 8. *Smerni koti $_tz$ v referenčnem KS. Črtkane premice pomenijo dejanske smerne kote normale površine.*
Fig. 8. *Directional angles of $_tz$ in the base CS. The dashed lines are real directional angles of the surface.*

smeri $_ty$ v delih krivulj z največjo ukrivljenostjo, ko os $_tx$ ni poravnana s krivuljo. Ti odmiki so tudi posledica izbire neoptimalnih parametrov vidnega vodenja.

Iz zavrtitvene matrike preslikave med baznim in delovnim KS izračunamo smerne kote osi $_tz$ v primerjalnem KS robota. S slike 8 je razvidno, da se smer osi $_tz$ spreminja v območju 5° okrog želene vrednosti, kar je posledica dejstva, da smo zanemarili silo trenja in da sile v smeri osi $_tx$ in $_ty$ niso enake nič.

4 SKLEP

Razvili smo sistem, ki je zmožen na temelju združevanja podatkov različnih zaznaval slediti neznani poti na neznani površini in ob tem vzdrževati stalen stik med površino in orodjem. Zaznavalo sile, nameščeno v zapestju robota, zagotovi informacijo o krajevni usmeritvi površine v točki dotika. Kamera v zapestju je uporabljena za sledenje neznane krivulje na površini. Predlagana metoda ne zahteva kalibracije kamere, zagotoviti je treba zgolj pravilno postavitev kamere glede na $_t$KS.

Sistem bi izboljšala uporaba merilne ure za merjenje *L*, namesto posrednega merjenja prek sile. Zaradi neznane natančne lege vrha orodja smo uporabili manjše vrednosti ojačanj za sledenje usmeritve površin, saj se zaradi nenatančne lege vrha

are some position errors in parts where the bending of the curve is large and the $_tx$ axis is not aligned with the curve. These errors can also be caused by non-optimal visual control parameters.

From the rotation matrix of the homogeneous transformation between the base CS and the $_t$CS direction the angles of the axis $_tz$ in the reference CS of robot were calculated. From Fig.8 it is evident that the direction of the axis $_tz$ is within a region of 5° around the desired value. The reason for this is that the frictional force is neglected and the forces in the direction of the $_tx$ and $_ty$ axes are not exactly zero.

4 CONCLUSION

We have developed a system based on sensor fusion that is able to track an unknown trajectory on an unknown surface and to maintain a constant contact between the tool and the surface. A wrist-mounted force sensor provides local information about the surface orientation at the point of contact, while the camera is used for tracking the unknown curve on the surface. The proposed method does not require camera calibration, only proper placing of the camera in the $_t$CS has to be ensured.

The system could be improved by a direct measurement of the compliant tool length. The unknown exact position of the top of the tool forced us to use smaller values of gains for the tracking-surface orientation. The inaccurate direct kinematics cause namesto čiste zavrtitve pojavijo še premiki v delovnem prostoru. Dodatna izboljšava bi bila tudi uporaba nekalibriranega prostorskega vida, saj bi s tem pridobili bolj celovito informacijo o razgibanosti površine, kakor jo omogoča zaznavalo sile.

translation in the task space when only the orientation is supposed to be done. Another improvement to the proposed system would be the use of an uncalibrated stereo vision system. In this case more global information about the surface dynamics could be acquired.

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Prejeto:
Received: 16.5.2005

Sprejeto:
Accepted: 29.6.2005

Odprto za diskusijo: 1 leto
Open for discussion: 1 year