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Naprava s pnevmatično aktivno površino: Tehnike krmiljenja lege togih objektov s povratno zvezo in brez nje

A Pneumatic Active-Surface Device: Open- and Closed-loop Control-Positioning Techniques for Rigid Objects

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Pomanjkanje proizvodnih tehnik za premikanje in spreminjanje usmerjenosti velikega števila majhnih predmetov je tehnološka ovira za tržni uspeh na različnih področjih mikro elektromehanskih sistemov (MEMS). V prispevku je predstavljen bistveno nov postopek avtomatizacije množičnega sočasnega rokovanja z majhnimi predmeti. Raziskana je naprava s pnevmatično aktivno površino (NPAP). Ustrezna izbira sile, ki jo povzroča pihanje ali sesanje zraka skozi cevke naprave z aktivno pnevmatično površino, povzroča želeno premikanje predmetov na aktivni površini naprave. Naprava omogoča veliko prilagodljivost in hitrost in jo lahko uporabimo za pozicioniranje, orientiranje, identifikacijo, sortiranje, podajanje in sestavljanje predmetov. Dodatno k temu lahko vodimo mnogo predmetov hkrati. Prispevek opisuje eksperimentalno delo, opravljeno na prototipu naprave s pnevmatično aktivno površino, posebej tehnike krmiljenja (s povratno zvezo in brez nje) lege togih objektov, manjših od 1 mm.

(Ključne besede: deli mali, manipulacija predmetov, naprave pnevmatične, zaznavanje predmetov, regulacija lege)

The current lack of manufacturing techniques for handling very high volumes of small objects presents a technology barrier to commercial success in various fields like micro-electromechanical systems (MEMS). A fundamentally new approach to automated, massive, parallel manipulation of small-sized parts is explored in this paper: the pneumatic active surface device (PASD). With the appropriate choice of force – caused by blowing or sucking air-flow through the tubes of the pneumatic active surface device – objects placed on the array can be moved in useful ways. Such a device offers great flexibility and speed and can be employed to position, orient, identify, sort, feed, and assemble parts or objects. Another advantage is that several objects can be controlled simultaneously. This paper describes experimental work on a prototype pneumatic active surface device, in particular an open-loop and closed-loop positioning control techniques for sub-millimeter rigid objects.

(Keywords: small parts, objects manipulation, pneumatic control equipment, position control)

0 UVOD

Množična proizvodnja miniaturnih komponent kakor so integrirana vezja, mikro elektromehanski sistemi (MEMS) ipd. terjajo bistvene izboljšave na področju rokovanja predmetov. Te komponente so izdelane na podlagi procesa mikroproizvodnje, ki izvira iz tehnologije zelo visoke integracije (ZVI - VLSI). Le ta omogoča proizvodnjo tisočev ali milijonov komponent hkrati. Naprava s pnevmatično aktivno površino (NPAP) uporablja nov postopek avtomatiziranega rokovanja predmetov. Namesto rokovanja posameznih

0 INTRODUCTION

The mass production of miniature components such as integrated circuits, micro-electromechanical systems (MEMS), etc. requires fundamental innovations in the handling of parts. These components are built using microfabrication processes derived from VLSI technology, which allows the manufacture of thousands or millions of components in parallel. A pneumatic active surface device (PASD) uses a new approach to automated manipulation of objects (parts): instead of handling a predmetov (npr. z robotskim prijemalom [12]) z uporabo naprave s pnevmatično aktivno površino premikamo mnoge predmete hkrati. Naprava s pnevmatično aktivno površino omogoča vzporedno in porazdeljeno zaznavanje in proženje in je še posebno primerna za rokovanje serijsko mikroproizvedenih predmetov, katerih majhne izmere (manj ko milimeter) in veliko število ne omogočajo konvencionalnega rokovanja (poberi in odloži) z robotskimi prijemali. V zadnjem času so bile razvite mnoge podobne naprave:

1. Programljivo polje sil je matrika velikega števila programljivih točk mikrogibanja ([1] in [5]). Pri krmiljenju gibanja predmetov po programljivem polju sil je uporabljena strategija »ožajočih se vzorcev« ([1], [2] in [7]) ob uporabi analize ravnotežnega stanja ([1] do [3]). Naprava je opisana v [1] in [2] in ima pomembne lastnosti, to so: občutljiva je na poškodbe in nima vgrajenih zaznaval. Zato za premikanje predmetov po njej ni mogoča izvedba krmiljenja s povratno zvezo. Naš postopek uporablja zaznavala tlaka, ki se uporabljajo za zaznavanje predmeta na NPAP, zato omogoča zaznavanje predmeta na osnovi njegove ploskve, s katero se dotika pnevmatično aktivne površine. Zato naš postopek omogoča izvedbo tehnik krmiljenja s povratno zvezo.
2. Navidezno vozilo [4] je zgrajeno iz celic, ki predstavljajo mehanizem z dvema prostostnima stopnjama. Za krmiljenje vsake izmed celic je uporabljen zapleten postopek krmiljenja, saj je za krmiljenje vsake celice potreben mikroprocesor (MC68HC11). Vsaka celica je informacijsko povezana z drugimi celicami s pomočjo serijske povezave RS232. Nemogoče si je predstavljati, koliko komunikacijske in računalniške pomoči bi bilo treba za izvedbo matrike z nekaj stotisočimi celicami, ki bi premikale mikroskopsko majhen predmet. Osnovna celica naše naprave (cevka in zazanavalo tlaka), ki je načrtovana za premikanje mikroskopsko majhnih delcev, je izvedena preprosteje, zato bi bil potreben en mikroprocesor (MC68000) za krmiljenje prek deset tisoč celic.
3. Prve mikroproizvedene celice in matrike na podlagi zračnega toka so bile predstavljene v [6], toda za njih ni poročil o uporabljenih strategijah krmiljenja predmetov po matriki. Naše tehnike krmiljenja omogočajo od oblike predmeta neodvisno krmiljenje osnovnih premikov in usmeritev s povratno zvezo in brez nje (translacija, rotacija) za toge in elastične predmete. Nekatera poročila o krmiljenju in rokovanju predmetov na programljivem polju sil so v [1] do [3] in [7] in so delno vplivala na razvoj naših tehnik krmiljenja.
4. Mnoge skupine raziskovalcev MEMS so zgradile aktuatorske matrike za mikromanipulacijo, ki so običajno zgrajene iz 'gibalnih točk'. Naprave so zgradili prej omenjeni avtorji ([1], [4] do [6] in v [8] do [11]).

single object directly, for example, with a robot gripper [12], a PASD can be used to move multiple objects simultaneously. This new automation device permits both parallel and distributed forms of sensing and actuation, and is particularly attractive for handling batch microfabricated objects, whose small dimensions (sub-millimeter) and large numbers do not allow conventional pick-and-place operations with robot grippers. Recently, several similar devices have been invented:

1. Programmable force field (massive parallel array of programmable micromotion pixels ([1] and [5])) uses a control strategy called "squeeze patterns" ([1], [2] and [7]) using equilibrium analysis ([1] to [3]). The device described in [1] and [2] has an important drawback because it is susceptible to damage and has no integrated sensors. Therefore closed-loop position control methods cannot be used for moving objects on a surface with programmable force fields. Our approach uses pressure sensors that sense an object on the surface of the PASD and allow the use of object recognition from the footprint of the object sensed by pressure sensors and also the use of closed-loop position techniques.
2. The Virtual Vehicle [4] uses a complicated control technique for each cell, this requires complete microprocessor (MC68HC11) control of a two-degree-of-freedom mechanical mechanism. Each cell is informationally linked to the other cells with a RS232 serial link. It is impossible to imagine how much communication and computer power would be needed in the case of an array of a few hundred thousand micromachined actuators (cells) for carrying near-microscopic objects. The basic cell (a tube and a pressure sensor) of our device, which is designed for carrying near-microscopic objects, is controlled in a simpler way, with only one microprocessor (MC68000) needed to control over ten thousand cells.
3. The first airflow-based micromachined cells and arrays were presented in [6]; however they did not publish any control strategy for moving the objects on the array. Our control techniques allow basic open-loop and closed-loop, rigid and flexible, object movements – translation, rotation, and flip – that are independent of the object's shape. Some reports of control and manipulation of the objects on programmable force fields are reported in [1], [2], [3] and [7] and have been partly influential on the development of our control techniques.
4. Several groups of MEMS researchers have designed and built actuator arrays for micromanipulation, which usually consist of "motion pixels". Devices were built by the previously mentioned authors [1], [4], [5], [6] and also by [8], [9], [10] and [11].

Opis celotnega prototipa NPAP in analiza stabilnosti togega objekta na površini naprave po Ljapunovovi metodi sta predstavljena v [13]. V tem prispevku, ki je drugi objavljen prispevek od treh na temo NPAP v Strojniškem vestniku, so opisane tehnike krmiljenja lege s povratno zvezo in brez nje za translacijo, rotacijo in obračanje togega objekta, manjšega od 1 mm na pnevmatični aktivni površini, podrobno opisani v [13]. Tehnike krmiljenja lege s povratno zvezo in brez povratne zveze za gibljive objekte pa bo objavljena v tretjem prispevku.

The complete prototype design of our PASD and a Lyapunov stability analysis of an object on the device was presented in [13]. The open-loop and closed-loop position control techniques for translating, rotating and flipping rigid, sub-millimeter objects are described in this paper, which is the second of three papers published in Journal of Mechanical Engineering on the subject of PASDs. Open-loop and closed-loop position control techniques for flexible objects on a PASD will be described in the third paper.

1 KRMILJENJE BREZ POVRATNE ZVEZE

1.1 Krmiljenje translacije

Najbolj robustno in uporabno translacijsko tehniko brez povratne zveze smo poimenovali “konvergenčni valovi”. Ta tehnika temelji na metodi krmiljenja brez povratne zveze za mehanični aktuator MEMS [1]. Omenjeno tehniko smo testirali za majhne objekte velikosti od 1 do 15 (3 krat 5) ploščine cevke s premerom 0,4 mm. Slika 1 prikazuje postopek delovanja “konvergenčnih valov”.

Ponavljajoči se krogi oziroma kvadrati sesajočih cevk (“valovi”) se pomikajo (konvergirajo) proti cevki, kjer je želena končna lega objekta. Vsi objekti, ki so znotraj področja, pokritega z valovi, se pomaknejo do želene cevke (lege). Iz vseh drugih cevk, ki niso v želeni legi ali znotraj konvergenčnega vala, piha. Ponavljajoči se konvergenčni valovi povzročijo tako silo kakor vibracije, ki so potrebne, da premikajo objekt na površini. Frekvenco valov lahko spreminjamo. Če je frekvenca previsoka, tedaj se objekt premika prehitro, kar povzroči, da se želena lega doseže s prenihajem. Frekvenca ponavljajočih se valov je odvisna od medsebojne dinamike objekta in površine (trenje med objektom in površino, višina objekta). Razdalja med dvema zaporednima konvergentnima valoma mora biti dolga vsaj toliko, kolikor je dolg objekt. Vzrok za to je v tem, da objekt stoji na mestu in se sploh ne premika, če pokriva sesajoče cevke dveh ali več zaporednih valov. Pogoj za premikanje objekta je, da je samo ena sesajoča cevka pokrita z objektom. Na drugi strani pa velja, da objekt pogosto odpihne s površine, če so vse cevke, ki jih pokriva objekt, postavljene na pihanje. Za večje objekte (npr. 5 krat 5 površin cevk) ena sesajoča cevka ni dovolj, da bi zadržala objekt na površini. Verjetno je treba povečati število sesajočih cevk pod takim večjim objektom; res pa je, da tega še nismo testirali.

Metoda krmiljenja translacije s konvergenčnimi valovi ima to pomanjkljivost, da lega objekta na površini ni merjena. Tako se lahko zgodi, da se objekt zatakne nekje na površini in ne doseže želene lege.

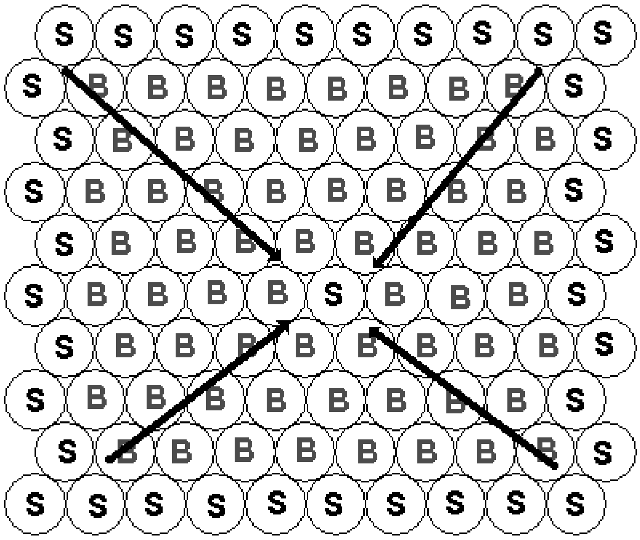
1 OPEN-LOOP CONTROL

1.1 Open-loop translation

The most robust and generally applicable method for the open-loop translation of objects is called “converging waves”. It is based on a method originally developed for a MEMS mechanical actuator array [1]. It has been tested and used for smaller objects, from 1 square pixel to 15 square pixels (3-by-5 pixels). The scheme of the converging waves procedure is shown in Figure 1.

Repetitive circles or squares of tubes sucking (“waves”) converge towards the tube (“pixel”) where the center of the object should land. All objects, which can be found within the area covered by the waves move towards the center tube (desired pixel) and stop in this position. All tubes except the center tube and the pixels of the converging sucking waves are set to blow. The repetitive converging waves generate both a force and a vibration, which are needed to move the object on the surface. The frequency of the waves can be changed. If the frequency is too high the object can move too quickly and this can result in overshooting the desired end-position. In fact the frequency of the value should be dependent on the dynamics of the object and the surface (friction between the surface and the object, the height of the object etc…). The distance between two successive converging waves must be at least as large as the length of the object. This is because if the object on the surface covers more sucking tubes in two successive waves at the same time then the element becomes locked into position and will not move at all. A condition for moving an element is that only one of the tubes covered by the object is set to suck. On the other hand, if all tubes below the object are set to blow then the element is easily blown away from the surface. For larger objects (for example 5-by-5 pixels) one sucking tube is not enough to prevent the object from being blown away. It is probably necessary to increase the number of sucking tubes in the case of larger objects on the surface; however, this has not yet been tested.

The open-loop translation converging wave method has a problem in that the position of the object is not sensed, so in the event that the object is stuck somewhere on the surface the object may not reach the desired destination.



Sl. 1. *Postopek "konvergenčnih valov" (S-sesanje, B-pihanje)*
Fig. 1. *"Converge waves" procedure (S-suck, B-blow)*

1.2 Krmiljenje vrtenja

Ta metoda se imenuje tudi "premikanje črte sesanja". Objekt vrtimo v ravnini NPAP okoli osrednje točke, ki jo definira uporabnik takole: operater izbere osrednjo točko, ki je v enem izmed vogalov objekta, nato izbere še želeno točko, ki je hkrati tudi konvergentni center za konvergentne valove. Črta med tema dvema točkama je nova želena lega roba objekta. Želena točka mora biti izbrana blizu enega izmed vogalov objekta, ki je čim dalje od osrednje točke. Želena točka mora biti izbrana v smeri želene rotacije. Med vrtenjem objekta vse cevke pihajo, razen tistih, ki tvorijo črto med osrednjo in želeno točko. Če je katera izmed cevk, ki sestavljajo omenjeno črto, pokrita z objektom, tedaj mora tudi ta cevka izvrševati ukaz pihanja. Če se to ne bi zgodilo, tedaj bi objekt miroval prisesan na površino. Seveda sta tako želena kakor osrednja točka vedno točki sesanja. Obenem se uporabijo ponavljajoči se konvergenčni valovi za nastanek vibracij na površini NPAP, ki se ožijo v smeri proti želeni točki. Te vibracije so pomembne zato, da preprečijo objektu z ostrimi robovi, da bi se zataknil v vdolbinah med vrstami cevk. Metoda je opisana in prikazana na sliki 2. Črta med cevkama osrednje in želene (konvergentno središče) točke pomeni črto sesanja. Krivulja na nasprotni smeri od osrednje točke sukanja objekta v smeri želene točke pomeni smer vrtenja okoli osrednje točke.

1.3 Krmiljenje preobračanja

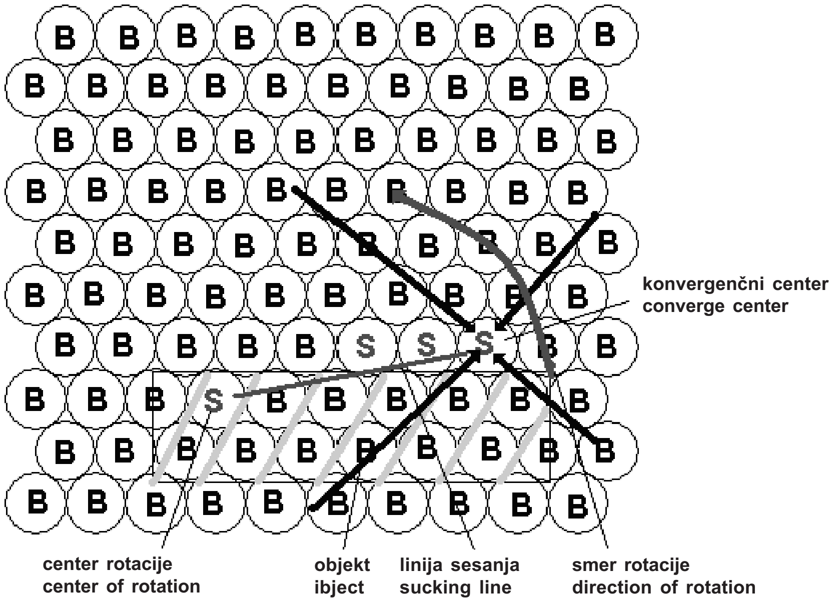
Preobračanje objekta pomeni, da je stran objekta, na kateri je pred obračanjem ležal objekt, potem obrnjena kvišku. Preobračanje tako pomeni gibanje, ki je zunaj ravnine aktivne površine in je zaradi

1.2 Open-loop rotation

This method is called "a moving sucking line". The procedure for rotating the object about a user-defined center point is as follows. First, the operator chooses the center point, which is on one of the corners of the object. The user also selects a desired point (converge center). The line between these two points is the new desired position for the edge of the object. The desired point has to be chosen close to (or in a neighborhood of) one of the corners of the object that is far away from the center point. The desired point also has to be in the direction of the desired rotation. During the rotation of the object all the tubes are set to blow except those forming a line between the center point and the desired point. If any of the tubes forming this line, other than the center of rotation, are covered by the object they must also be set to blow. If they do not blow they will lock the object down preventing it from moving as desired. Of course, both the center and the desired points have to be set to suck. In order to induce the required vibration there are also repetitive waves of sucking tubes converging towards the desired point. The vibrations are needed to prevent an object with sharp edges from getting stuck in gaps between the rows of tubes. The method described is illustrated in figure 2. The line between the center point (tube) and the desired point (converge center or the desired tube) represents the sucking line. The curve from the opposite side of the center point of the object to the direction of desired point shows the direction of rotation about the center point of the object.

1.3. Open-loop flipping

Flipping an object consists of turning an object around so that the side originally facing the active surface will be facing away from the surface. This involves motion out of the plane of the active



Sl. 2. *Krmiljenje vrtenja z metodo "premikajoče se črte sesanja" (B-pihanje, S-sesanje) (objekt je predstavljen s pravokotnikom, ki je pobarvan s sivimi črtami)*
Fig. 2. *Open-loop rotation about the center with "moving sucking line" method (B-blow, S-suck). The object is represented by the rectangle with gray strips*.

tega mnogo bolj zahtevna, kakor sta vrtenje in premik objekta na sami ravnini. Vdolbine med cevkami po navadi povzročajo težave pri tehnikah krmiljenja brez povratne zveze, ker objekt ne more gladko drseti po površini in se zaradi tega pogosto zatakne na njej. Zato smo pri poprej opisanih metodah uporabljali konvergentne valove in s tem vibracije, da bi preprečili zatikanje ostrih robov objektov v vdolbinah aktivne površine. V primeru preobračanja objekta pa so prav te vdolbine potrebne. V samem začetku preobračanja se mora oster in relativno raven rob objekta poravnati z vdolbino med cevkami, vse cevke vzdolž roba objekta pa izpolnjujejo ukaz sesaj. Nato se izvede ukaz "pihaj" na vse cevke, ki jih pokriva objekt. Ta ukaz povzroči, da se objekt dvigne kvišku za 90 stopinj in obmiruje na svojem ostrem robu, zataknjenem v vdolbini. Po tem dvigu objekta kvišku se izpolni ukaz "sesaj na vseh cevkah na drugi strani objekta", kar povzroči, da se objekt prevrže in obleži na aktivni površini na drugi strani objekta. Preobračanje objekta kaže slika 3.

Naslednji postopek natančno opisuje preobračanje objekta vzdolž črte sesanja:

- Korak 1: prisesaj objekt na površino in začni sesati na črti sesanja (sl. 3)
- Korak 2: začni pihati skozi cevke, najprej v tretji, nato v drugi vrsti pod objektom. Objekt bo počasi začel drseti proti vdolbini med črto sesanja in prvo vrsto, ki jo pokriva objekt. Po tej aktivnosti se bo oster rob objekta zataknil v vdolbini in se nekoliko dvignil, kakor je prikazano na sliki 4.
- Korak 3: prva vrsta cevk je v tem trenutku izpolnila ukaz, "pihaj". Objekt se dvigne na svoj oster rob vzdolž črte sesanja, tako da

surface and is therefore more challenging than rotation and translation within the plane. The gaps between the tubes are usually a complicating factor in the open-loop translation and rotation control techniques because an object cannot slide smoothly and often gets stuck at the edges or in the gaps. Vibration techniques such as converge waves have been used to prevent objects from sticking with their sharp edges in the gaps. In the case of a flipping operation the grooves are desired or even required. Before initiating the flip a sharp (and relatively straight) edge of the object is aligned with a groove in the surface and the tubes along this edge are set to suck. Then the object is lifted up to approximately 90 degrees by blowing through all the tubes that were covered by the object and were sucking the object a moment before. After the object has been lifted up to 90 degrees and rests on the sharp edge suction is initiated on this other side of the sucking line so the object is laid down on the other side. The flipping of the object is shown in Figure 3.

The step-by-step procedure for how to flip an object along a line of sucking tubes is as follows:

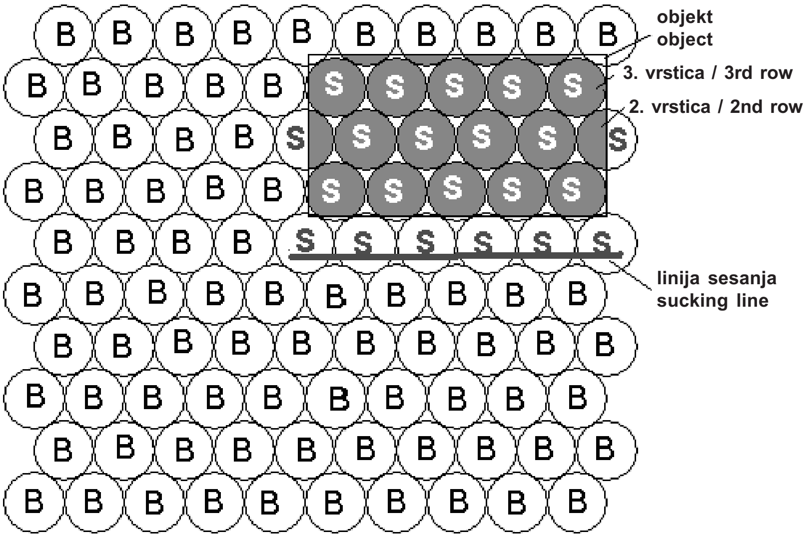
- Step 1: suck the object and then set to suck on the sucking line (Figure 3).
- Step 2: set to blow, first to the third and then to the second row, of the object. The object slowly slides towards the gap between the sucking line and the first row covered with the object. After this step the sharp edge of the object is stuck in the gap once the object is lifted up a little as shown in Figure 4.
- Step 3: the first row covered by the object is immediately set to blow. The object is lifted up on the sharp edge on along the sucking line so the

oklepa s površino kot okoli 90 stopinj. Pihajoči zračni tokovi ob obeh straneh objekta pomagajo stabilizirati objekt v pokončni legi (sl. 4).

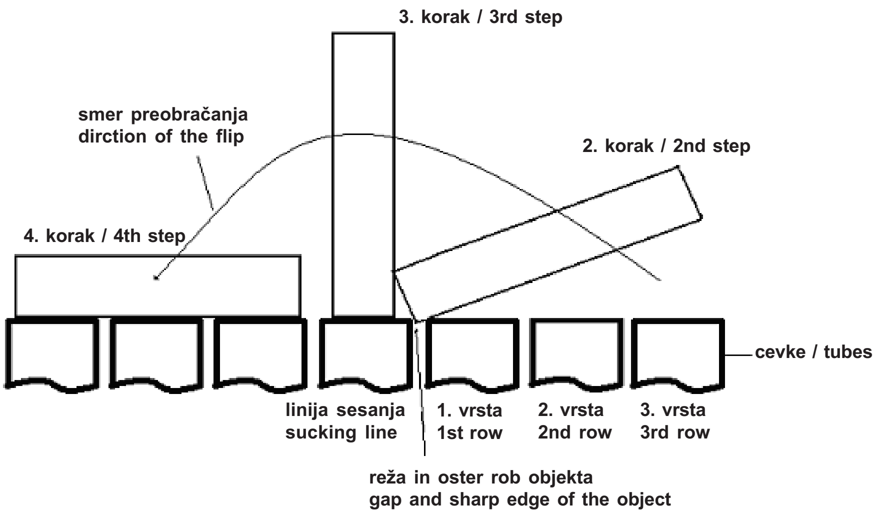
- Korak 4: cevke na drugi strani linije sesanja spremenijo smer iz pihanja v sesanje, kar povzroči prisesanje objekta na površino (sl. 4).

object makes an angle of approximately 90 degrees with the surface. The air streams (blowing out) on each side of the object may assist in stabilizing the object in this position (Figure 4).

- Step 4: the tubes on the other side of the sucking line are changed from blowing to sucking and the object is sucked down onto the surface (Figure 4).



Sl. 3. *Začetna lega pri obračanju (B-pihanje, S-sesanje)*
Fig. 3. *A starting position for the flipping of the object (B-blow, S-suck)*



Sl. 4. *Preobračanje objekta*
Fig. 4. *The flipping of the object*

2 KRMILJENJE S POVRATNO ZVEZO

2.1 Krmiljenje premika s povratno zvezo

Da bi preprečili nenadzorovano zatikanje objekta na površini NPAP, kakor je to pogost primer pri tehnikah krmiljenja brez povratne zveze, smo v samo krmiljenje vključili informacijo o dejanski legi objekta. Osnovni koraki krmiljenja premika s povratno zvezo so:

2 CLOSED-LOOP CONTROL

2.1 Closed-loop translation

It is desirable to incorporate feedback information regarding the position of the object to prevent the object from getting stuck on the PASD, as is often the case when open-loop control techniques are used. The basic steps of the closed-loop translation control are:

- Korak 1: uporabnik definira želeno oziroma končno lego (cilj).
- Korak 2: meritev lege objekta.
- Korak 3: načrtovanje in izvedba premika objekta v novo lego.
- Korak 4: meritev nove lege.
- Korak 5: koraka 3 in 4 je treba ponoviti, če objekt ni dosegel želene lege, sicer se postopek ustavi.

V koraku 1 uporabnik določi želeno lego z uporabo miške na zaslonu osebnega računalnika, ki je uporabljen za komunikacijski vmesnik človek - stroj. Želena lega se preračuna v številko cevke, uporabljene za končno točko premika krmiljenja s povratno zvezo.

Korak 2 in 4 opravljata enako delo, to je meritev lege objekta na NPAP in določata dolžino objekta v smeri X in Y.

Korak 3 računa napake lege v smeri X in Y. Nato določi dolžino črte sesanja, ki je uporabljena kot prožilna sila za drsenje objekta proti želeni legi. Dolžina linije sesanja za premik v smeri Y je enaka pravokotni projekciji objekta na os X NPAP. Podobno velja za premik objekta v smeri X, kjer je dolžina črte sesanja enaka pravokotni projekciji objekta na os Y NPAP.

Korak 5 izvaja odločitev na podlagi izračuna položajnega odstopka (razlike med želeno in dejansko vrednostjo) v smeri X in Y. Če sta oba položajna odstopka v smeri X in Y enaka nič, tedaj je objekt dosegel želen položaj in postopek se s tem konča. Če želena lega ni dosežena, tedaj se ponovijo koraki 3, 4 in 5.

Razvili smo dve tehniki premika s povratno zvezo, ki se razlikujeta zgolj v koraku 3:
- običajni premik s povratno zvezo (OPPZ) in
- premik z navidezno povratno zvezo (PNPZ).

2.1.1. Tehnika krmiljenja običajnega premika s povratno zvezo (OPPZ)

Pri tej tehniki se objekt premika samo za eno črto naenkrat v smer X ali Y, dokler se ne doseže želena lega. Prvi korak 3 se izvede s proženjem črte sesanja v smeri X, kar povzroči, da se objekt premakne v smer X za eno črto (vrsto). Takoj za tem se izvedeta koraka 4 in 5, šele po tem pa se spet izvede korak 3, vendar tokrat v smeri Y za eno črto sesanja (sl.5a). Opisan vrstni red izvajanja posameznih korakov se izvaja, dokler želen položaj ni dosežen. Če je, npr. želena lega v smeri X dosežena prej kakor pa v smeri Y, tedaj se postopek nadaljuje samo za premike v smeri Y. Med izvajanjem črte sesanja v koraku 3 se izvajajo tudi konvergenčni valovi (gl. 1.1), da bi se preprečilo zatikanje objekta na površini NPAP. Konvergenčni valovi so osrednjeni v tisto izmed

- Step 1: user defines the desired end-position (target).
- Step 2: the position of the object is measured.
- Step 3: motion is planned and actuation is used to move the object.
- Step 4: the new position is measured.
- Step 5: if the object has not reached the desired position steps 3 and 4 are repeated, otherwise the process is stopped.

In step 1 the user clicks with a mouse on a desired position on the screen of the PC, which is used as a man-machine communication interface. The position of the mouse is translated into the tube number, which is used as an end point of the closed-loop translation.

Steps 2 and 4 are the same. They sense the position of the object on the PASD and calculate the length of the object in X and Y direction of the PASD.

Step 3 calculates a position error in the X and Y directions. It also calculates the direction and length of the “sucking line”, which is used as an actuating force to slide the object towards the desired position. The length of the sucking line for a movement in the Y direction is the same as the rectangular projection of the object onto the X axis of the PASD. It is similar for a movement in the X direction, where the length of the sucking line is equal to a rectangular projection of the object onto the Y axis of the PASD.

Step 5 is used as a decision statement. It calculates the X- and Y-position errors: the differences between the actual and desired positions in both X and Y directions. If both X- and Y-direction errors are equal to zero the object has reached, the desired position and the procedure finishes. If the desired position is not reached, then steps 3, 4 and 5 are repeated.

The two closed-loop translating techniques according to two types of actuating procedures in step 3 were developed:
- a regular closed-loop translation (RCLT),
- a quasi closed-loop translation (QCLT).

2.1.1. Regular closed-loop translation (RCLT) technique

In this technique the object is moved one line at a time in either the X or the Y direction until the desired destination has been reached. First, step 3 is executed by sucking one line in the X direction resulting in the object sliding in the X direction by one line. Next, step 4 and 5 are executed. After that step 3 is executed again, but only for one sucking line, this time in the Y direction (see Figure 5a). The described procedure is repeated until the destination is reached. If, for example, the desired X position is reached before the desired Y position, then each of the following steps will only move the object in the Y direction. Converge waves (described in subsection 1.1) are also executed to prevent the object from getting stuck during the execution of the sucking line steps (step 3). The converging waves are centered on the end point of the sucking line with a greater obeh končnih točk črte sesanja z večjo razdaljo do roba objekta. Hitrost premikanja objekta ob uporabi OPPZ je sorazmerno majhna, ker je po vsakem umeščanju s črto sesanja treba izvesti meritev lege objekta.

Slike 6a do 6e prikazujejo premikanje objekta (1,5mm × 0,9mm) od začetne do želene lege na stvarni NPAP z OPPZ. Slike (6f do 6j) kažejo meritve lege z mikroračunalnikom, ki so prikazane v istih trenutkih, kakor jih prikazuje zgornja vrsta slike 6. S slike 6 je razvidno, da meritve lege vedno ne ustrezajo dejanskim legam objekta na NPAP. Razlog za napačni merilni podatek je ta, da robovi objekta niso ostri, kakor tudi spodnja stran objekta ni ravna ploskev, kar povzroči, da nekatere cevke NPAP niso tesno pokrite z objektom. S slik 6c in 6d lahko razberemo, da se je objekt začasno zataknil na površini. Razrešitev tega problema je prikazana na sliki 6e, kjer so konvergenčni valovi poskrbeli za dovolj vibracij, kakor je opisano v prejšnjem odstavku.

2.1.2. Tehnika krmiljenja premika z navidezno povratno zvezo (PNPZ)

Tehnika PNPZ je bila razvita, da bi povečali hitrosti premikanja objekta na NPAP. Računanje in izvajanje črte sesanja (korak 3) v smereh X in Y se nadaljuje brez merjenja lege objekta na NPAP med črtami sesanja. Dve črti sesanja (ena v X, druga v smeri Y) sta generirani izmenoma in premikata objekt proti želeni legi (sl. 5b). Šele ko pričakujemo, da objekt doseže želeno lokacijo, izmerimo dejansko lego objekta. Če želena lega ni dosežena, se izračunajo in izvedejo nove črte sesanja v smeri proti želeni legi v eni ali obeh smereh. Tehnika PNPZ je krmiljenje brez povratne zveze na časovnem koraku med obema meritvama lege. Vsaka črta sesanja izvaja tudi konvergentne vibracije (gl. 1.1), da bi se preprečilo zatikanje objekta na površini NPAP. Konvergenčni valovi vzbujalnih vibracij imajo začetni premer izmere treh cevk, kakor je to bilo izvedeno pri OPPZ. Dosedanje izkušnje so pokazale, da se objekt sploh ni zatikal na površini. Mnogokrat pa se je zgodilo, da se je objekt nenadzorovano preobrnil na površini ob zatikanju, medtem ko se je izvajal postopek premika krmiljenja brez povratne zveze med dvema zaporednima meritvama dejanske lege objekta, nato pa je preprosto nadaljeval pot do želene vrednosti. Število nenadzorovanih obračanj se lahko močno zmanjša, če nekoliko znižamo nadtlak pihanja zraka skozi cevke.

Hitrost premikanja objekta ob uporabi PONPZ je bila približno 1cm/s, kar je desetkrat hitreje kakor v primeru uporabe OPPZ. Hitrost premikanja objekta je odvisna od dinamične interakcije med NPAP in objektom. S povečevanjem razlike nadtlaka pihanja

distance to the edge of the PASD than the other end point of the same sucking line. The movement of objects using the RCLT method is slow because after each sucking line operation (step 3) a complete position measurement is required.

Figures 6a–6e show the movement of an object (1.5mm × 0.9mm) from the start position to the desired position on a real PASD with RCLT. Figures (6f–6j) in the lower row show the measurement of position with a microcomputer and are presented on the screen of the computer at the same time as the real object position is shown in the upper row of Figure 6. From Figure 6 we can see that the measurement positions do not always match the real positions of the object on the PASD. This is because either the edges of the object are not sharp or the bottom side of the object is not a regular plane, which means that some tubes on the PASD are not tightly covered with the object. Figures 6c and 6d show that the lower left corner of the object got temporarily stuck. The problem is solved as in Figure 6e with the use of converge waves described above.

2.1.2. Quasi closed-loop translation (QCLT) technique

The QCLT technique was developed with the aim of increasing the speed of the object on the PASD. The calculation and execution of the sucking line (step 3) in the X and Y directions continues without measuring the object position on the PASD in between waves. In fact, two sucking waves (one in the X direction, another in the Y direction) are created simultaneously and they move the object towards the desired position (see Figure 5b). Once the object should have reached the desired location the position is measured and compared to the desired position. If the desired position is not reached a new set of waves are calculated and executed in one or two directions, as needed. The QCLT technique is an open-loop translating procedure during the time interval between two position measurements. To prevent the objects from getting stuck somewhere on the PASD every sucking line also has its own converging excitation (see subsection 1.1). The converge-wave has a starting diameter of 3 pixels, as was the case for the RCLT technique. Experience has shown that objects do not get stuck at all; it is more likely that the object flips uncontrollably if it gets stuck for a moment during the open-loop-translating procedure between two position measurements and then continues on the path demanded by the sucking line waves. The number of uncontrolled flips can be decreased if the blow pressure is slightly reduced.

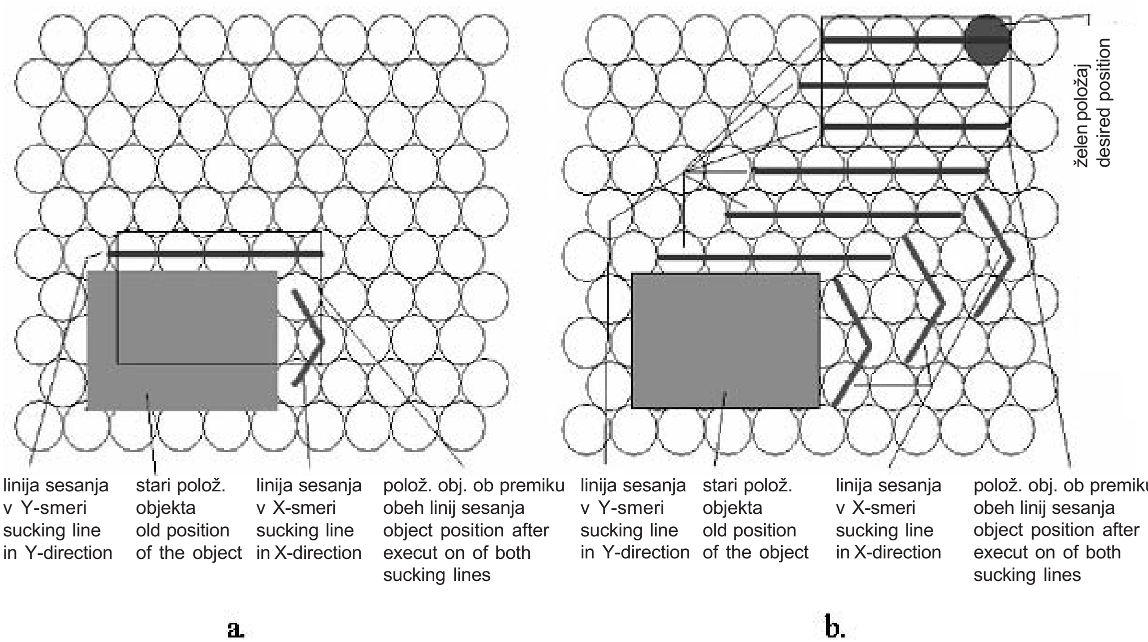
The speed of the object movement using the QCLT technique is approximately 1 cm/sec, which is a tenfold improvement over the RCLT technique. The speed of the object movement depends on the dynamic interaction between the PASD and the object.

in podtlaka sesanja v cevkah lahko povečamo hitrost premikanja objekta po površini. Hitrost pa se zmanjša, če je objekt težji, oziroma površina objekta ali NPAP bolj hrapava, ker je v obeh primerih večje trenje. Če bi črta sesanja potovala prehitro v primerih povečanega trenja med objektom in površino, tedaj bi prišlo do manjšega prenihaja prek želene lege ali pa bi bilo celo mogoče, da bi objekt odpihnilo s površine NPAP, ker objekt ne bi mogel dovolj hitro slediti premikajočim se črtam sesanja.

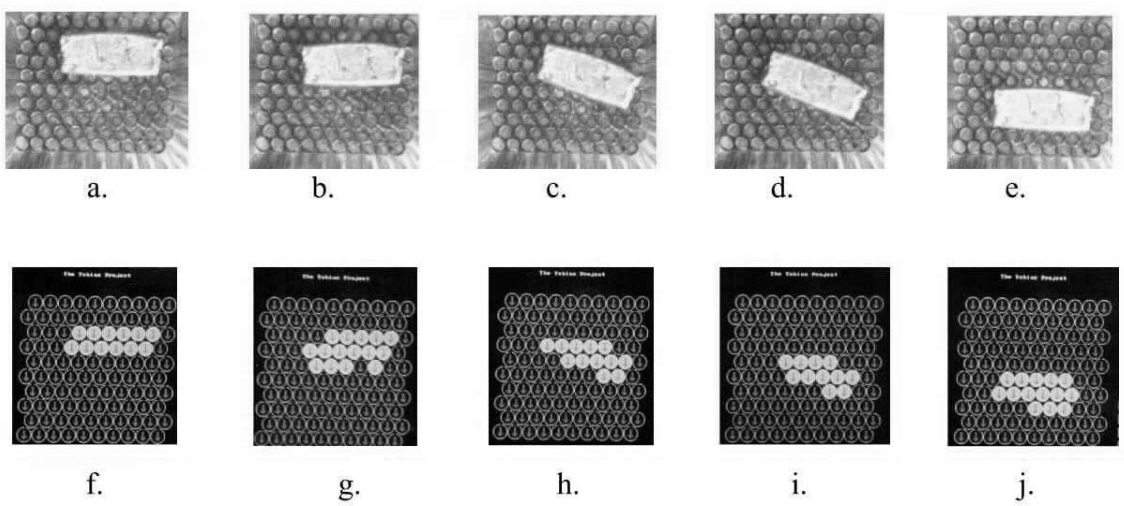
V splošnem lahko rečemo, da PNPZ omogoča hitrejše premikanje objekta po površini (1 do 1,5cm/s), medtem ko OPPZ omogoča le počasnejše (0,1 do 0,15 cm/s), vendar natančnejše pozicioniranje objekta na površini NPAP.

Increasing the difference between positive (blow) and negative (suck) pressures can increase the speed of the object's movement. The speed can be reduced if the object is heavier or if the surface is rough; in both cases the friction is higher. If the sucking line waves are travelling to fast in these high-friction situations the objects may slightly overshoot the desired position or it may even be blown off the PASD because the object cannot follow the sucking lines fast enough.

In general the QLCT technique allows enables the faster movement of objects (1–1.5 cm/sec), while the RCLT technique allows slower (0.1–0.15 cm/sec) but more accurate positioning of the object on the PASD.



Sl. 5. *Premik objekta s tehniko OPPZ (a) in PNPZ (b)*
Fig. 5. *Translating the object with the RCLT (a) and QCLT (b) techniques*



Sl. 6. *Premik objekta na stvarni NPAP z OPPZ*
Fig. 6. *Movement of the object on a real PASD with RCLT*

2.2 Krmiljenje vrtenja s povratno zvezo

Tehnika krmiljenje vrtenja s povratno zvezo je v bistvu razširitev poprej opisane tehnike vrtilnega krmiljenja brez povratne zveze, predstavljene v podpoglavju 1.2. Osnovni koraki postopka izvajanja krmiljenje vrtenja s povratno zvezo so naslednji:

- Korak 1: uporabnik poda želeni kot zasuka vrtenja.
- Korak 2: meritev lege objekta.
- Korak 3: prožilno polje cevk premakne objekt do želenega kota vrtenja.
- Korak 4: meritev nove lege objekta.
- Korak 5: postopek se konča, razen če objekt ni opravil predpisanega kota zasuka. Takrat se morata koraka 3 in 4 ponoviti.

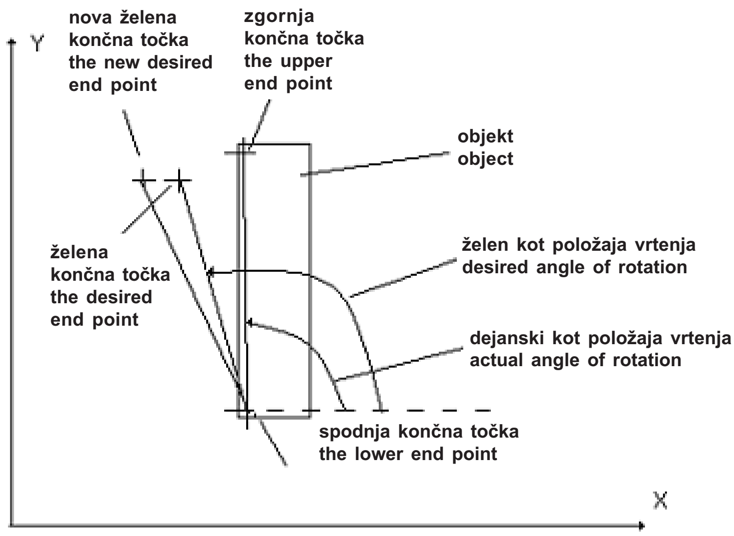
Uporabnik določi dve točki: vrtilno središče, ki je blizu enega izmed koncev objekta, in novo želeno lego drugega konca objekta. To se opravi s pritiskom na miško na mesto na zaslonu, kjer se prikazuje lokacija objekta, izmerjena v koraku 1. Nato računalniški algoritem izračuna želeni kot zasuka. Dejanski kot se izračuna iz črte, narejene med obema koncema objekta v koraku 1. Računalniški algoritmi izmerijo in izračunajo tri točke: želeno vrtilno središče, dejanski konec objekta in želeni konec objekta v korakih 2 in 4 (sl. 7). Nato sledi v koraku 4 izvedba proženja, ki vrti objekt za želeni kot zasuka. Če se objekt ni zasukal za želeni kot zasuka ali zasedel točko želene lege, se koraka 3 in 4 ponovita, ampak tokrat z novim želenim kotom zasuka. Algoritem konstruira novo želeno črto, ki sloni na prvotni želeni točki, povečani za en premer cevke v smeri stran od dejanske črte. Ponavljanje korakov 3 in 4 z novo želeno črto, ki je nekoliko stran od premikanega objekta, je treba v

2.2 Closed-loop rotation

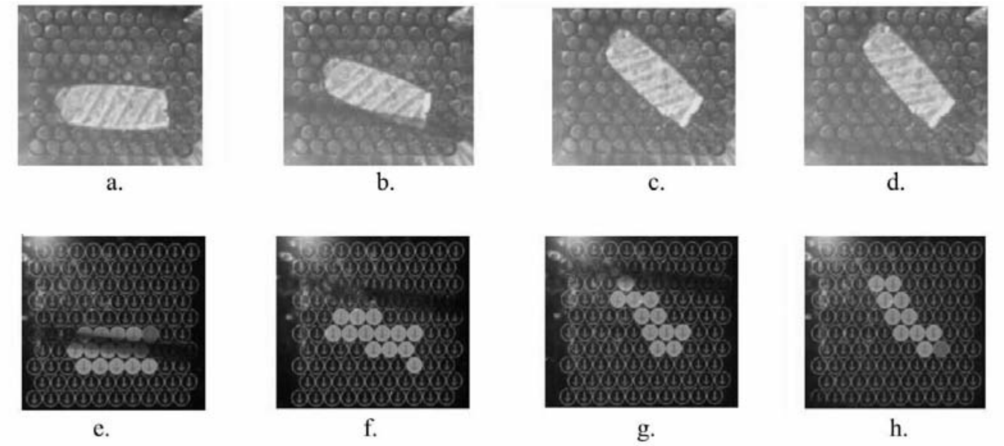
The closed-loop rotation technique is an extension of the previously described open-loop rotation technique from subsection 1.2. The basic steps of closed-loop rotation are:

- Step 1: user gives the desired angle of rotation.
- Step 2: the position of the object is measured.
- Step 3: the actuators are used to move the object to the desired angle of rotation.
- Step 4: the new position of the object is measured.
- Step 5: if the object has not reached the desired angle of rotation then steps 3 and 4 are repeated, otherwise the procedure is stopped.

A user has to define two points: the center of rotation (located near one end of the object) and the new, desired location of the other end of the object. This is done by clicking with the mouse on a screen showing the object sensed in step 1. Based on this a computer algorithm calculates the desired angle. The actual angle is calculated from the line drawn between both ends of the objects as observed in step 1. The computer algorithm measures and calculates all three points (an actual or desired center of rotation, an actual end of the object and a desired end of the object) in steps 2 and 4 (see figure 7). An actuation is executed to move the object from the actual angle to the desired angle (step 4). If the object has not reached the desired angle or occupied the desired position point the algorithm repeats steps 3 and 4, but with a new, desired angle of rotation. The algorithm constructs a new, desired line based on the originally desired end point that is increased by one pixel away from the actual line. Repeating steps 3 and 4 with a new, desired angle that is a little further away from the controlled object is frequently required when the object does not



Sl. 7. *Definicije kotov vrtenja*
Fig. 7. *The definition of rotation angles*



Sl. 8. *Vrtenje objekta na stvarni NPAP*
Fig. 8. *Rotation movement of the object on the real PASD*

primeru, ko objekt nima ravne spodnje površine. Če sta želeni kot zasuka ali želena točka dosežena, naprava konča postopek v koraku 5. Konvergenčni valovi, opisani v podpoglavju 1.1 se ves čas izvajajo med krmiljenjem vrtenja objekta s povratno zvezo, da bi preprečili zatikanje objekta z ostrimi robovi na površini. Konvergenčni valovi so usmerjeni v želeno točko črte sesanja.

Slike 8a do 8j kažejo vrtenje objekta okoli njegovega spodnjega desnega vogala za 60 ločnih stopinj na dejanski NPAP. S slik 8h in 8j vidimo, da se je središče vrtenja premaknilo za en premer cevke v smer Y. Razlog za to je v tem, da robovi v bližini spodnjega levega vogala niso ostri, tako da nekatere cevke NPAP pod objektom niso tesno pokrite.

2.3 Krmiljenje preobračanja s povratno zvezo

Tehnika obračanja objekta na površini NPAP z krmiljenjem s povratno zvezo sloni na tehniki, opisani v podpoglavju 1.3. Razlika med obema tehnikama je v tem, da računalniški algoritem posredno določi, ali se je objekt obrnil ali pa ne. Potreben pogoj za preobračanje objekta na površini pri obeh tehnikah je: oster rob objekta in obstoj vdolbine med cevkami na površini NPAP. Ker nekateri robovi objektov niso dovolj ostri ali vdolbine med cevkami na površini niso dovolj globoke ali pa kombinacija obeh omenjenih razlogov, se zgodi, da v okoli 25 % primerov tehnika krmiljenja brez povratne zveze ne deluje. Tako postane zelo pomembna identifikacija, ali je bila zadana naloga obračanja objekta opravljena ali ne. Uporabili smo metodo za posredno določevanje, ali se je objekt preobrnil na površini NPAP.

- Korak 1: določitev objekta z meritvijo v njegovi prvotni legi.
- Korak 2: poskus obračanja objekta ob uporabi tehnike obračanja s krmiljenjem brez povratne zveze.
- Korak 3: določitev objekta na novi lokaciji z meritvami.
- Korak 4: Nova in stara lega objekta se primerja: če sta legi narazen za več ko tri vrste, tedaj se je

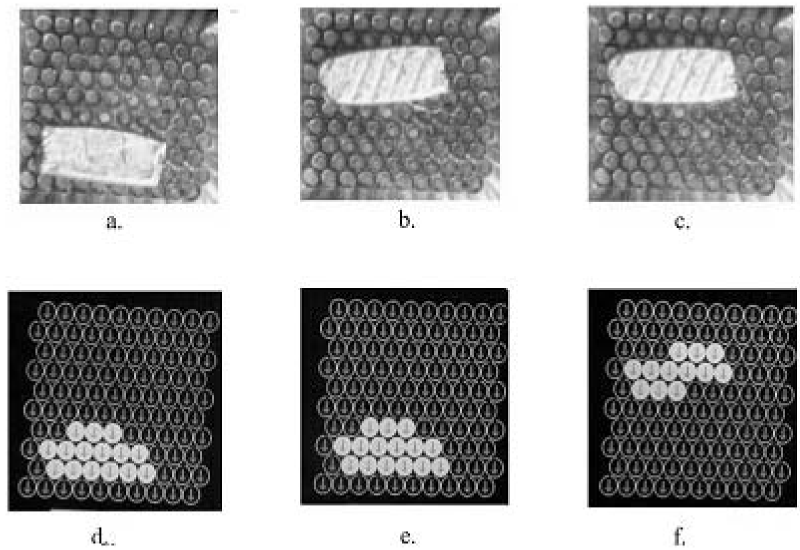
have a flat bottom. If the desired angle or desired position has been reached the algorithm finishes the procedure in step 5. Converge waves (described in subsection 1.1) are also executed to prevent the object (particularly objects with sharp edges) from getting stuck during the execution. The converge waves are centered on the desired end-point of the sucking line.

Figures 8a–8j show the rotation of the object about the lower right corner by 60 degrees on the real PASD. Figures 8h and 8j show that the measured center of rotation is moved slightly (by 1 pixel) in the Y direction. The reason for this is that the edges of the object close to the lower right-hand corner are not sharp, so the tubes of the PASD under the object are not tightly covered.

2.3 Closed-loop flipping

The closed-loop flipping technique uses the same basis as the open-loop flipping technique described in section 1.3. The only difference between them is that a computer algorithm is used to determine whether the object is flipped or not. The necessary conditions for flipping are the same in both techniques: a sharp edge of the object and an existing gap between tubes on the PASD. Because some of the edges on the object are not sharp enough or some of the gaps between the tubes are not deep enough, or a combination of both reasons, it happens in approximately 25% of cases that the open-loop flipping technique does not work. Therefore, it becomes important to identify whether or not the task has been completed successfully. An indirect method is used to determine if the object has actually been flipped:

- Step 1: the object is sensed in its original position.
- Step 2: an attempt is made to flip the object using the open-loop flipping technique.
- Step 3: the object is sensed in its new position.
- Step 4: the new and old positions are compared: if they differ by more than three rows the object



Sl. 9. *Krmiljenje preobračanja objekta s povratno zvezo na dejanski NPAP*
Fig. 9. *A closed-loop flipping of the object on a real PASD*

objekt obrnil pravilno (nadaljevanje s korakom 5), če ne, algoritem ponovi celotni postopek od koraka 1 do 4.

- Korak 5: konec.

S povečevanjem nadtlaka pihanja lahko povečamo odstotek uspešno izvedenih poskusov obračanja brez povratne zveze. Vendar se moramo zavedati, če preveč povečamo nadtlak pihanja skozi cevke, se poveča tudi število neuspelih poskusov obračanja zaradi tega, ker se objekt odpihne s površine NPAP.

Slike 9a do 9f kažejo obračanje objekta s krmiljenjem s povratno zvezo na dejanski NPAP. Sliki 9a in 9d kažeta lego objekta pred obračanjem. Sliki 9b in 9e kažeta lego objekta trenutek po tem, ko se je izvedlo obračanje, preden se je novo izmerjena lega prikazala na zaslonu. Sliki 9c in 9f kažeta lego objekta po končanem obračanju objekta s krmiljenjem s povratno zvezo.

3 UPORABA ORODIJ NA NPAP

Orodja so objekti, ki jih postavimo na NPAP zato, da bi povečali učinkovitost delovanja z objekti. Na primer, obe uporabljeni tehniki krmiljenja togih objektov s povratno zvezo in brez nje imata nekaj pomanjkljivosti, posebej sorazmerno počasen premik objekta po površini, pa tudi razpoznavanje objekta je omejeno zgolj na pravokotno projekcijo objekta na površini NPAP; torej višine objekta ne moremo izmeriti. Z uporabo posebej načrtovanih orodij se lahko tema dvema problemoma izognemo, kakor je pojasnjeno v nadaljevanju.

3.1 Povečanje hitrosti pomika objekta na NPAP

Na začetku poglavja 2 smo omenili, da trenje med objektom in površino NPAP omejuje hitrost pomika togega objekta na površini. Torej hitrost pomika objekta na površini lahko povečamo, če

has flipped correctly (continue with step 5), if not then the algorithm repeats the whole procedure from step 1 to step 4.

- Step 5: the end.

Using a higher positive (blowing) pressure can increase the percentage of successfully completed open-loop flipping attempts. Unfortunately, however, the number of cases where the object is blown off the surface is also increased when the pressure is increased too much.

Figures 9a–9f show closed-loop flipping on a real PASD. Figures 9a and 9d show the position of the object before the flipping. Figures 9b and 9e show the position of the object a moment after the flipping, prior to measuring the position with the computer. Figures 9c and 9f show the position after the closed-loop flipping of the object.

3 USING TOOLS ON PASD

Tools are objects, other than the parts being handled, which can be placed on the PASD. They are used to improve the handling or processing of the parts. For example, both open-loop and closed-loop position-control techniques for rigid objects have some disadvantages: movement of the part is relatively slow, and recognition of the part's size is limited to the footprint, which means the third dimension (height) cannot be observed. With the use of specially designed tools it is possible to overcome these two problems as explained below.

3.1 Increasing the speed of a movement on the PASD

As mentioned at the start of section 2, it is mainly the frictional force between the object and the PASD that limits the speed of an object moving on the PASD. So, if the frictional force can be reduced the speed of nam uspe zmanjšati trenje med njima. Zmanjševanje hrapavosti površine je ena izmed možnosti, ki pa po drugi strani preprečuje izvajanje obračanja objekta na taki površini (gl. 1.3). Uspešna rešitev tega problema je, da uporabimo namensko orodje, ki zelo zmanjša hrapavost površine NPAP in posledično zmanjša tudi trenje med površino NPAP in objektom. To namensko orodje je preprost gibljiv plastični trak, ki se uporabi za pot med trenutno in želeno lego objekta. Plastični trak mora biti zelo tanek in gibljiv. Naslednji koraki algoritma opisujejo postopek za povečanje hitrosti objekta na NPAP (sl. 10):

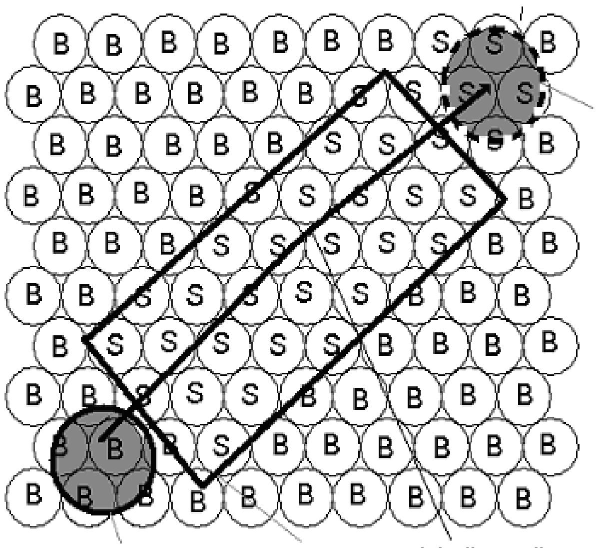
- Korak 1: Postavi gibljiv trak PVC primerne izmere na mesto med trenutnim in želenim položajem objekta. Trak je mogoče premikati po površini NPAP z uporabo posebnih tehnik, razvitih za pomik gibljivih objektov, ki bodo razložene v naslednjem prispevku.
- Korak 2: Izmeri lego traku in postavi vse cevke pod trakom na sesanje, kar povzroči, da je trak utrjen na mestu v naslednjih korakih.
- Korak 3: Vse preostale cevke okoli traku morajo pihati.
- Korak 4: Objekt se odlepi in oddrsi s trenutne lege proti želeni legi zato, ker pod objektom začne pihati iz cevk, na želeni legi na drugi strani traku pa hkrati cevke sesajo.
- Korak 5: Objekt prepotuje oziroma drsi z ene strani na drugo stran traku v kanalu pihajočega zraka na vsaki strani traku, ki objektu omogoča potovanje zgolj po traku v "trenutku".

Hitrost pomikanja togega objekta na NPAP z gibljivim trakom PVC je okoli 10 do 15 cm/s, kar je

motion can be increased. Lowering the friction of the whole surface is not an option, as this will prevent operations like the flipping of objects (see subsection 1.3). A successful solution to this problem is the use of a special tool that can dramatically reduce the roughness of the PASD and, therefore, the frictional forces between the PASD and the object during the movement. This special tool is a simple flexible plastic band, which is used as a path between an actual position and a desired position of the object on the PASD. The plastic band has to be very thin and flexible. The method of increasing the speed of the movement on the PASD is described in the next steps (see figure 10):

- Step 1: Place the flexible PVC band of proper dimensions between the actual and desired positions of the object. It is possible to move it from one place on the PASD to another place using special techniques developed for handling flexible objects.
- Step 2: Detect the position of the band and set all the covered tubes of the PASD on suck, so the band is fixed during the next steps.
- Step 3: All other tubes on both sides of the band have to be set to blow.
- Step 4: The object is released from its current position by switching to blow in the tubes that were covered by the object, and setting to suck the tubes of the desired position on the other side of the PVC band at the same time.
- Step 5: The object travels (slides) from one side to another side of the band practically instantaneously.

The speed of the movement using the described method is approximately 10–15 cm/sec,



Sl. 10. *Povečanje hitrosti pomika objekta na NPAP z uporabo traku*
Fig. 10. *Increasing the speed of the object on the PASD with the band*

desetkrat hitreje od do sedaj opisane najhitrejše PNPZ, opisane v podpoglavju 2.1.2. Opravili smo teste s plastičnim trakom dolžine 6 mm, ker smo bili omejeni s površino NPAP (5 mm × 5 mm). Menimo, da bi lahko trak podaljšali za večkrat ob zadovoljivih rezultatih premikanja objekta.

3.2 Nastavljanje lege objekta na gibljivem traku

V postopku, opisanem v prejšnjem podpoglavju, smo uporabili trak kot drsno površino na NPAP za hiter pomik objekta prek traku. Gibljiv trak z gladko površino se lahko uporabi tudi za nastavljanje lege objekta na traku. Predlagana metoda je krmiljenje premikanja togega objekta brez povratne zveze na vrhu traka PVC. Majhno trenje med objektom in trakom, ki leži na površini NPAP, omogoča delovanje postopka. Slika 11 prikazuje delovanje prej omenjenega postopka:

- Korak 1: Gibljiv plastični trak postavimo na NPAP in objekt postavimo na trak.
- Korak 2: Cevke sesajo na mestu želene lege (približno na sredini traku), drugod pa cevke pihajo.
- Korak 3: Objekt potuje (drsi) z višje lege traku, ki ga sestavljajo pihajoče cevke pod trakom v smeri depresije na traku, ki jo sestavljajo sesajoče cevke zaradi kombinacije gravitacijske sile in majhne sile trenja.
- Korak 4: Če se depresija na traku premika, se z njo premika tudi objekt.

Hitrost pomika objekta s tem postopkom je okoli 1 do 1,5 cm/s. Seveda je ta metoda krmiljenje brez povratne zveze po legi, kar lahko povzroči neljube zaplete, objekt ne sledi depresiji zaradi različnih razlogov.

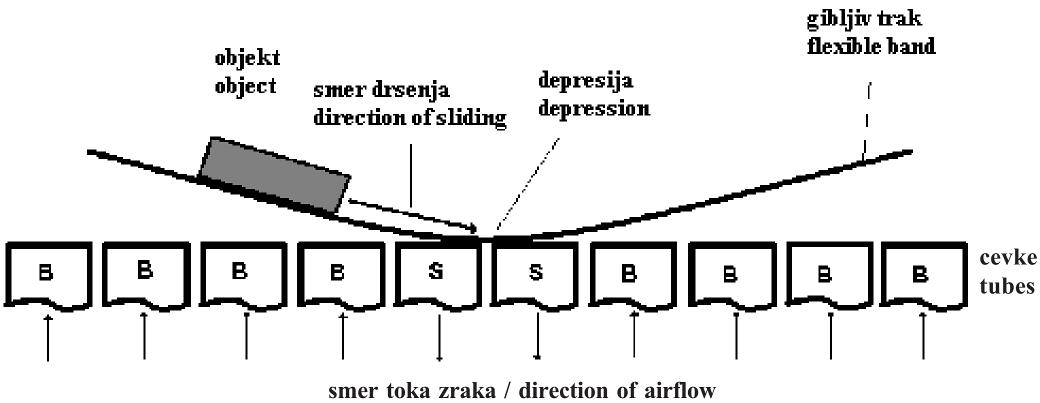
which is 10 times greater than the QCLT method described in subsection 2.1.2. Tests were made with a 6-mm length of the plastic band because of the limitations of the square area (5 × 5 mm) of the PASD. But we believe that the length of the band could be several times longer than that used in these tests.

3.2 Positioning of an object on a flexible band

In the previous method the band was used as a “sliding” surface on the PASD to bring the object from one end to the other in a short period of time. A flexible low-friction surface can also be used to position an object within the surface or the band, as described in this section. The proposed method is an open-loop control technique for moving an object on the top of the flexible plastic surface. A low frictional force between the object and the band lying on the PASD is essential. Figure 11 shows how this control technique works:

- Step 1: The flexible material is placed on the PASD, and the object is placed on top of the flexible material or the band.
- Step 2: The valves are set to suck somewhere in the middle of the band (where the object should be going to) and set to blow on each side of the sucking region.
- Step 3: The object travels from the “hills” above the blowing tubes to the depression made by the sucking tubes because of the gravitational force combined with the low friction between the object and the flexible band.
- Step 4: If the depression on the band is moving the object follows it on the top of the band.

The speed of movement with this method is approximately 1–1.5 cm/sec. Of course this kind of method is open-loop control technique so it could happen that the object does not always slide to the depression on the band generated by the sucking tubes.



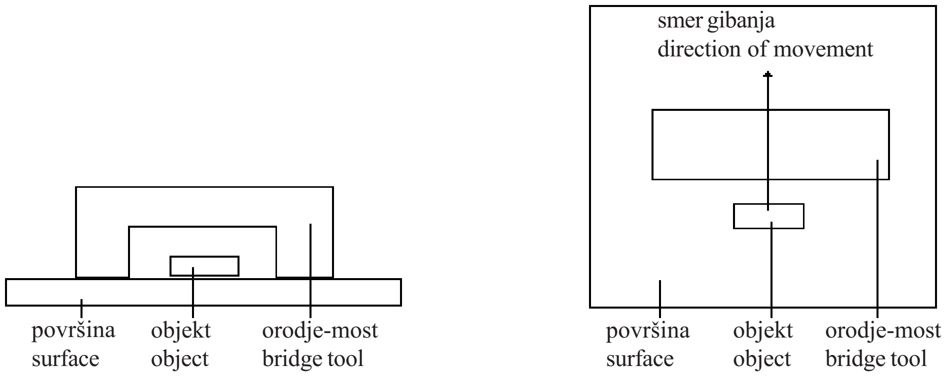
Sl. 11. *Nastavljanje lege objekta na traku*
Fig. 11. *Positioning of the object on the band*

3.3 Mostično orodje

Na NPAP je mogoče izmeriti z zaznavali pritiska zgolj pravokotno projekcijo objekta na površino. Tako lahko določimo zgolj dvoizmerno sliko objekta na površini, medtem ko tretja izmera (višina) ostane nepoznana. Mostično orodje se uporabi za določitev višine objekta. Če lahko objekt drsi pod mostom, lahko ocenimo, da je višina objekta nižja od razdalje med površino in nižjim spodnjim delom mostičnega orodja. Na ta način se da grobo določiti višino objekta. Če uporabimo več različnih mostičnih orodij zaporedoma, lahko določimo višino objekta dokaj natančno. Slika 12 prikazuje uporabo mostičnega orodja.

3.3 A "bridge" tool

It is only possible to measure the footprint of an object on the PASD with pressure sensors. It is, therefore, only possible to obtain a two-dimensional picture of the object on the surface; the third dimension (height) remains unknown. A bridge tool is used for determining the height of objects. If an object can go under the bridge we know that the height of the object is smaller than the distance between the surface and the lower part of the bridge tool. In this way it is possible to roughly determine the height of an object. It is of course necessary to have several different bridge tools to be able to distinguish between different height groups. Figure 12 shows the use of the bridge tool.



Sl. 12. *Uporaba mostičnega orodja za določitev višine*
Fig. 12. *Use of the bridge tool to determine the object's height*

4 SKLEP

Ta prispevek prikazuje najprej preskuse tehnik krmiljenja brez povratne zveze po legi, utemeljene na konvergenčnih valovih za premik, vrtenje in obračanje togega objekta, manjšega od 1 mm na prototipu NPAP. Ker so omenjene tehnike imele težave pri krmiljenju, kar je bila posledica pogostih zatikanj objektov na površini NPAP, smo v krmiljenje brez povratne zveze vključili informacijo o legi objekta. Drugi del prispevka tako opisuje krmiljenje s povratno zvezo lege za premik, vrtenje in obračanje togega objekta na površini NPAP. Obe tehniki krmiljenja objekta po legi na NPAP, predstavljeni v prvih dveh delih prispevka, imata naslednji pomanjkljivosti: relativno počasno premikanje objekta in razpoznavanje velikosti in oblike objekta iz odtisa (dotikalne površine med objektom in površino NPAP), tako da tretje izmere (višine) objekta ni bilo mogoče določiti. Zato zadnji del prispevka opisuje uporabo posebnih "orodij" (prilagodljivi trak in gibljivi"most"), ki zaobideta omenjena problema.

Naslednji prispevek na temo NPAP v naslednji številki Strojniškega vestnika bo prikazal natančen opis tehnik krmiljenja brez povratne zveze in krmiljenje s povratno zvezo lege za gibljive objekte na NPAP.

4 CONCLUSION

This paper first presents the prototype design and experiments of the open-loop position-control techniques based on converging waves for translating, rotating and flipping rigid sub-millimeter objects on a PASD. It is also desirable to incorporate the feedback information regarding the position of the rigid object to prevent the object getting stuck on the PASD as it is often the case when open-loop control techniques are used. The next part of the paper shows closed-loop position-control techniques developed for translating, rotating and flipping rigid parts on the PASD. The open-loop and closed-loop position-control techniques for rigid objects have some drawbacks: relatively slow movement of the part and a limited ability to recognise the size of the part; so the third dimension cannot be determined. The last part of the paper describes the use of specially designed tools – a flexible band and a bridge tool – to overcome these two problems.

Open-loop and closed-loop position-control techniques for flexible objects will be described in the next issue of Journal of Mechanical Engineering.

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