© Strojniški vestnik 48(2002)6,332-354
ISSN 0039-2480
UDK 621.867.8:531.3:681.51/.52
Izvirni znanstveni članek (1.01)
© Journal of Mechanical Engineering 48(2002)6,332-354
ISSN 0039-2480
UDC 621.867.8:531.3:681.51/.52
Original scientific paper (1.01)

Naprava s pnevmatično aktivno površino: Tehnike krmiljenja gibljivih predmetov

A Pneumatic Active-Surface Device: Control Techniques for Flexible Objects

Suzana Uran - Riko Šafarič

Pomanjkanje proizvodnih tehnik za rokovanje z velikim številom majhnih predmetov pomeni tehnološko oviro za tržni uspeh na različnih področjih mikroelektromehanskih sistemov (MEMS). V prispevku je predstavljen bistveno nov postopek avtomatizacije množičnega hkratnega rokovanja z majhnimi predmeti. Raziskana je naprava s pnevmatično aktivno površino (NPAP), ki omogoča veliko gibljivost in hkratno krmiljenje velikega števila predmetov. Pihanje ali sesanje zračnega toka skozi cevke naprave z aktivno pnevmatično površino povzroča želeno premikanje predmetov na aktivni površini naprave. Ta prispevek opisuje eksperimentalno delo, opravljeno na prototipu naprave s pnevmatično aktivno površino. V njem obravnavamo tehnike krmiljenja brez povratne zveze za premik in vrtenje gibljivih predmetov. Zaradi motenj, ki povzročajo odstopanja od želenega gibanja, smo razvili tudi krmiljenje premika gibljivih predmetov brez povratne zveze ob hkratnem krmiljenju vrtenja s povratno zvezo.

(Ključne besede: deli mali, rokovanje s predmeti, naprave pnevmatične, zaznavanje predmetov, krmiljenje)

The current lack of manufacturing techniques for very-high-volume handling of small objects presents a technology barrier to commercial success in various fields like micro-electro-mechanical systems (MEMS). A fundamentally new approach to the automated, massive, parallel manipulation of small-sized parts is explored in this paper. We have investigated a pneumatic active-surface device (PASD) that offers great flexibility and simultaneous control of several objects. By either blowing or sucking air through the tubes of the PASD we can cause objects placed on the array to be moved in useful ways. This paper describes our experimental work on a prototype PASD. Open-loop control techniques for translation in two degrees of freedom and the rotation of flexible objects on a PASD are considered. Due to disturbances that cause deviations to the desired motion, open-loop translation control with closed-loop rotation control was also developed.

(Keywords: small parts, objects manipulation, pneumatic cnotrol equipment, object sensing, control techniques)

0 UVOD

Množična proizvodnja miniaturnih komponent, kakršna so integrirana vezja, mikroelektromehanski sistemi (MEMS) ipd. zahtevajo bistvene izboljšave na področju rokovanja s predmeti. Te komponente so izdelane na temelju postopka mikroproizvodnje, ki izvira iz tehnologije VLSI. Le ta omogoča proizvodnjo tisoč ali milijon komponent hkrati. Naprava s pnevmatično aktivno površino (NPAP) uporablja nov postopek avtomatiziranega rokovanja predmetov. Namesto rokovanja s posameznimi predmeti (npr. z robotskim prijemalom [12]) z napravo s pnevmatično aktivno površino premikamo mnoge predmete hkrati. Naprava s

0 INTRODUCTION

The mass production of miniature components such as integrated circuits, micro-electro-mechanical systems (MEMS), etc. requires fundamental innovations in parts handling. 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 object (part) manipulation. Instead of handling a single object directly, for example, with a robot gripper [12], a PASD can be used to move multiple objects simultaneously. This new aupnevmatično aktivno površino omogoča vzporedno in porazdeljeno zaznavanje in vzbujanje in je še posebno primerna za rokovanje s serijsko mikroproizvedenimi predmeti, katerih majhne izmere (manj kot milimeter) in veliko število ne omogočajo običajnega rokovanja (pick and place) z robotskimi prijemali. V zadnjem času so bile razvite mnoge podobne naprave:

1. Programljivo polje sil je matrika velikega števila programljivih točk mikrogibanja [1], [5]. Pri krmiljenju gibanja predmetov po programljivem polju sil je uporabljena strategija »ožajočih se vzorcev« [1], [2], [7] ob uporabi analize ravnotežnega stanja [1] do [3]. Naprava je opisana v [1], [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 podlagi 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 s preostalimi celicami s serijsko povezavo RS232. Nemogoče si je predstavljati, koliko komunikacijske in računalniške pomoči bi bilo potrebno za izvedbo matrike z nekaj sto tisoč celicami, ki bi premikale mikroskopsko majhen predmet. Osnovna celica naše naprave (cevka in zaznavalo tlaka), ki je načrtovana za premikanje mikroskopsko majhnih delcev, je izvedena preprosteje, zato bi bil potreben en mikroprocesor (MC68000) za vodenje prek deset tisoč celic.
3. Prve mikroproizvedene celice in matrike na podlagi zračnega toka so bile predstavljene v [6], toda o njih ni poročil o uporabljenih strategijah krmiljenja predmetov po matriki. Naše tehnike krmiljenja omogočajo od oblike predmeta neodvisno krmiljenje osnovnih premikov s povratno zvezo in brez nje in zavrtitev 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 mikrorokovanje, ki so običajno zgrajene iz ‘gibalnih točk’. Naprave so zgradili prej omenjeni avtorji ([1], [4] do [6] in v [8] do [11]).

Opis celotnega prototipa NPAP in analiza stabilnosti togega objekta na površini naprave po Ljapunovovi metodi sta predstavljena v [13]. Tehnike za premikanje s povratno zvezo in brez nje,

tomation device permits parallel and distributed, 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], [5]) has a control strategy called “squeeze patterns” [1], [2], [7] using equilibrium analysis [1] to [3]. The device described in [1], [2] has an important disadvantage 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 the programmable force fields. Our approach uses pressure sensors that are used to sense an object on the surface of the PASD, which allows the use of object-recognition from the footprint of the object sensed by pressure sensors as well as the use of closed-loop position techniques.
2. The Virtual Vehicle [4] uses a complicated control technique that requires a complete microprocessor (MC68HC11) to control a two-degree-of-freedom mechanical mechanism. Each cell is linked with the other cells via a RS232 serial link. It is impossible to imagine how much communication and computing power would be needed for 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 to carry near-microscopic objects is controlled in a simpler way, so that only one microprocessor (MC68000) is needed to control over ten thousand cells.
3. The first airflow-based micromachined cells and arrays were presented in [6], but no control strategy for moving objects on the array was published. Our control techniques allow basic open-loop and closed-loop rigid and flexible object movements (translation, rotation, flip) that are independent of the object’s shape. Some reports of the control and manipulation of objects on programmable force fields are reported in [1] to [3] and [7], and these have been partly influential in 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”. These devices were built by the previously referred to authors ([1], [4] to [6], and also by [8] to [11]).

The complete prototype design of a PASD and a Lyapunov stability analysis of an object on the device has been presented in [13]. The open-loop and closed-loop position-control techniques for vrtenje in preobračanje togih predmetov, manjših od 1 mm, so opisane v [14]. V tem prispevku, objavljenem v Strojniškem vestniku pa predstavljamo tehnike krmiljenja s povratno zvezo in brez nje za premikanje in vrtenje gibljivih predmetov na NPAP.

1 GIBANJE GIBLJIVIH PREDMETOV NA NAPRAVI S PNEVMATIČNO AKTIVNO POVRŠINO (NPAP)

Gibanje predmetov na napravi s pnevmatično aktivno površino (NPAP) je zelo zanimivo zaradi širokega razreda nalog pakiranja in zaradi tega, ker gibljivi predmeti, kakršni so polivinilasti trakovi, izboljšujejo gibanje togih predmetov na NPAP [14]. Za premikanje gibljivih predmetov v obliki tankih polivinilastih trakov so bile na NPAP razvite in preizkušene različne strategije krmiljenja. Različne materiale, kakor sta papir in polivinil, z različnimi debelinami smo preskusili v ta namen. Preskusi so pokazali, da je za sedanjo velikost NPAP (4 x 4 mm) običajen 75 g/m^2 papir pretog. Najbolje se je obnesla dovolj tanka, 0,5 mm debela, polivinilasta folija. Dolžina tipičnega traku, uporabljenega za preskuse, je bila enaka približno 5-kratni dolžini NPAP, medtem ko je bila širina tipičnega traku enaka približno 60 odstotkom širine NPAP.

Strategijo gibanja gibljivih predmetov, ki je obravnavana v tem poglavju, smo imenovali strategija ‘gosenice’. Strategija ‘gosenice’ je koračen postopek krmiljenja. Gibanje gibljivega predmeta (traku) je gibanje z majhnimi diskretnimi koraki. Pri tem je en korak sestavljen iz zaporedja podkorakov, ki so določeni z značilnim razporedom sesanja in pihanja cevk NPAP. Na začetku je obširna obravnava krmiljenja brez povratne zveze, na koncu prispevka pa je predstavljen primer krmiljenja s povratno zvezo gibljivega predmeta na NPAP.

1.1 Krmiljenje gibanja brez povratne zveze

Obravnavamo ravninsko gibanje na površini NPAP. Ravninsko gibanje ima tri prostostne stopnje gibanja in je v splošnem opisano s premikom vzdolž osi x, premikom vzdolž osi y in vrtenjem okoli osi z referenčnega koordinatnega sistema. Zato je v nadaljevanju predstavljeno krmiljenje brez povratne zveze vzdolžnega in vrtilnega gibanja.

1.1.1 Gibanje vzdolž dolžine traku

Gibljivost predmeta, ki ga premikamo, je zelo pomembna za strategijo premikanja ‘gosenice’. Za obliko traku je značilna majhna širina in velika dolžina. Zato je gibljivost traku največja vzdolž dolžine traku. Posledica tega je, da je strategija gibanja ‘gosenice ‘ najprimernejša za gibanje vzdolž dolžine traku. Na drugi strani pa je zaradi majhne

translation, rotation and flipping of a sub-millimeter rigid object has been described in [14]. And finally, the open-loop and closed-loop control techniques for the translation and rotation of flexible objects on the PASD are described in this paper, the third in a series published in the Journal of Mechanical Engineering.

1 THE MOTION OF FLEXIBLE OBJECTS ON THE PNEUMATIC ACTIVE-SURFACE DEVICE (PASD)

The motion of flexible objects on the PASD is of great interest in a wide range of packing tasks and because flexible objects, such as polyvinyl foil bands, improve the motion of rigid-body objects on the PASD [14]. Control strategies for the motion of flexible objects in the form of thin bands were developed and tested on the PASD. Different materials, such as paper and polyvinyl foil with different thickness were tested for this purpose. The experiments showed that for the existing size of the PASD (4 x 4 mm), normal 75 g/m^2 paper is too rigid. Sufficiently thin (0.5 mm) polyvinyl foil gave the best performance in the experiments. The length of a typical band used in the experiments was approximately five times the length of the PASD, while the width of a typical band used was approximately 60% of the PASD’s width.

The motion-control for flexible objects on the surface of the PASD is considered in this section. The motion control strategy for flexible objects is called a “caterpillar” strategy. The caterpillar strategy is a step-by-step control procedure. The motion of the flexible object (the band) is a motion in small, discrete steps. One step is the result of a sequence of substeps. Substeps are defined by a characteristic pattern of blowing and sucking actions of the PASD. Open-loop motion control for flexible objects is extensively discussed at the beginning, and an attempt at a closed-loop motion control for flexible objects is presented at the end of the paper.

1.1 Open-Loop Control of Motion

Planar motion on the surface of the PASD is considered. Planar motion has three degrees of freedom (DoF) and is, in general, described by a translation along the x-axis, a translation along the y-axis and a rotation about the z-axis of a reference coordinate system. Therefore, translational and rotational open-loop control is presented in the following subsections.

1.1.1 Translational Motion Along the Length of the Band

The flexibility of the object to be moved is of great importance for the caterpillar control strategy. The shape of the band is characterized by a narrow width and a long length. Consequently, the flexibility of the band is the greatest along the length of the band. Therefore, the caterpillar motion control strategy is natural (the most suitable) for translational motion along the length of the širine traku gibljivost traku vzdolž širine zelo majhna. Zato strategije gibanja 'gosenice' ne moremo uporabiti neposredno za gibanje vzdolž širine traku in zato neposredna uporaba strategije 'gosenice' vodi le do enoprostostnega vzdolžnega gibanja na NPAP. Manjkajoča prostostna stopnja gibanja je izvedena z bolj zapleteno uporabo strategije gibanja 'gosenice', ki je opisana v razdelku 1.1.3.

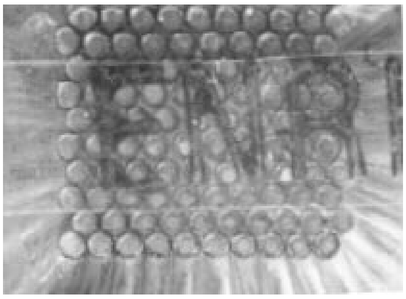
Referenčni koordinatni sistem je postavljen v levi spodnji vogal NPAP, tako da leži ravnina x-y koordinatnega sistema na površini NPAP in tako da leži os x referenčnega koordinatnega sistema vzdolž vrstic cevk NPAP. Lastni koordinatni sistem traku je pritrjen v levi spodnji vogal traku, tako da leži os x lastnega koordinatnega sistema vzdolž dolžine traku. Tako je gibanje traku vzdolž dolžine traku v lastnem koordinatnem sistemu traku definirano kot gibanje vzdolž osi x lastnega koordinatnega sistema. Po definiciji pomeni vzdolžno gibanje naprej gibanje v pozitivni smeri, medtem ko gibanje nazaj pomeni gibanje v negativno smer vzdolž osi gibanja.

Slika 1 prikazuje trak PVC na NPAP in zaznavanje traku na NPAP.

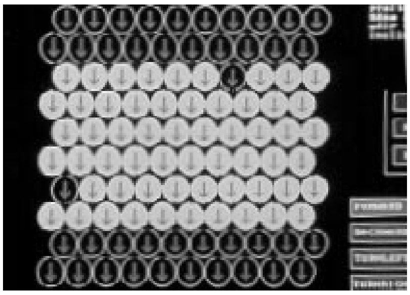
band. On the other hand, due to the narrow width the flexibility of the band along the width of the band is very low. Therefore, the caterpillar motion control strategy cannot be directly applied for translational motion along the width of the band and the direct application of a caterpillar strategy leads to only a one DoF translational motion on the PASD. The missing DoF of the translational motion is implemented by a more complex application of the caterpillar control strategy, which is described in section 1.1.3.

A reference coordinate system is attached to the left-hand bottom corner of the PASD so that the x-y plane of the reference coordinate system lies on the surface of the PASD and the x-axis of the reference coordinate system is directed along the rows of tubes of the PASD. An eigen-coordinate system is attached to the left-hand bottom corner of the band so that the x-axis of the eigen coordinate system is directed along the length of the band. So translational motion along the length of the band is in the eigen-coordinate system of the band defined as translational motion along the x-axis of the eigencoordinate system. By definition, translational motion forward means motion in the positive direction while translational motion backward means motion in the negative direction of the motion axis.

Fig. 1 shows the PVC band on the PASD, and its position detection.



a.



b.

Sl. 1. *a) Trak na NPAP in b) zaznavanje traku na NPAP*
Fig. 1. *a) The band on the PASD and b) position detection of the band*

En korak gibanja vzdolž dolžine traku je sestavljen iz zaporedja petih podkorakov. V nadaljevanju je en korak gibanja vzdolž dolžine traku predstavljen za primer, ko je usmerjenost lastnega koordinatnega sistema traku enaka usmeritvi referenčnega koordinatnega sistema.

Zaporedje podkorakov za gibanje naprej vzdolž dolžine traku je:

- **Podkorak 1**: Najprej sesajo vse cevke in s tem ustvarjajo negativni tlak.

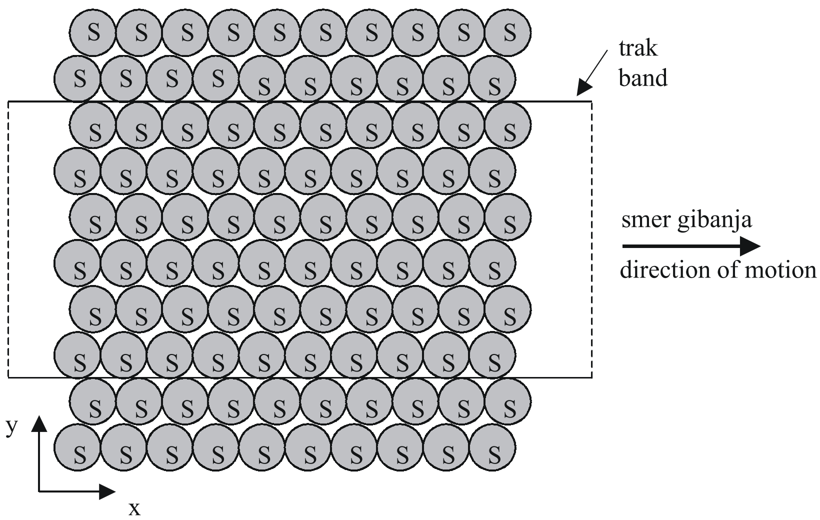
V podkoraku 1 trak leži tesno pritisnjen na površino NPAP (slika 2). Črtkane črtice na sliki 3 označujejo smer sile, ki deluje na trak, zaradi sesanja NPAP. Zaradi sesanja vsake cevke se pojavi krajevna sila na trak. Celotna sila na trak je enaka vsoti vseh krajevnih sil, ki so

One step of translational motion forward along the length of the band consists of a sequence of five substeps. In the following, one step of translational motion forward along the length of the band, for the case when the orientation of the band eigen-coordinate system is the same as the orientation of the reference coordinate system is presented.

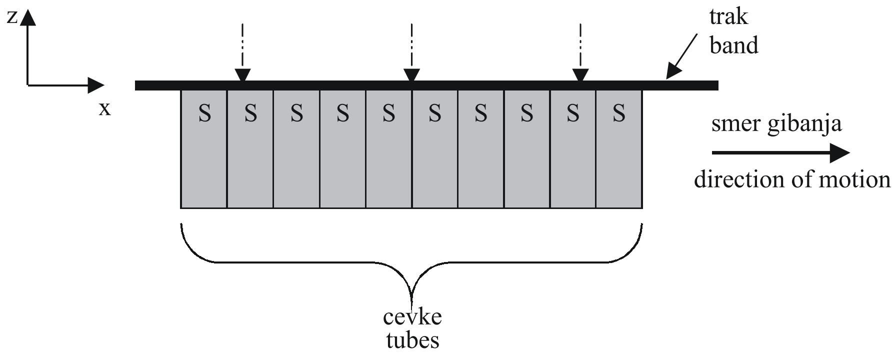
A sequence of substeps for translational motion forward along the length of the band is:

- **Substep 1**: Initially all the tubes are sucking, thereby producing a negative pressure.

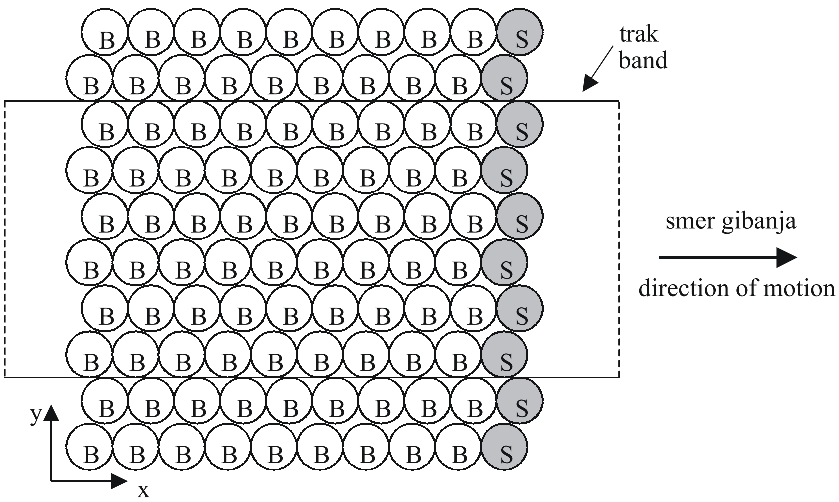
The band lies tightly pressed against the surface of the PASD in substep 1 (Fig. 2). Dashed arrows represent the direction of the force acting on the band due to the sucking action of the PASD in Figure 3. A local force on the band appears due to the sucking action of each tube. The total force acting on the band is a result of all



Sl. 2. *Podkorak 1 za vzdolžno gibanje desno (pogled od zgoraj)*
Fig. 2. *Substep 1 for translational motion right (top view)*



Sl. 3. *Trak leži tesno pritisnjen na NPAP*
Fig. 3. *The band lies tightly pressed to the PASD*



Sl. 4. *Podkorak 2 za vzdolžno gibanje desno (pogled od zgoraj)*
Fig. 4. *Substep 2 for translational motion right (top view)*

enakomerno porazdeljene po površini traku (polje sil).

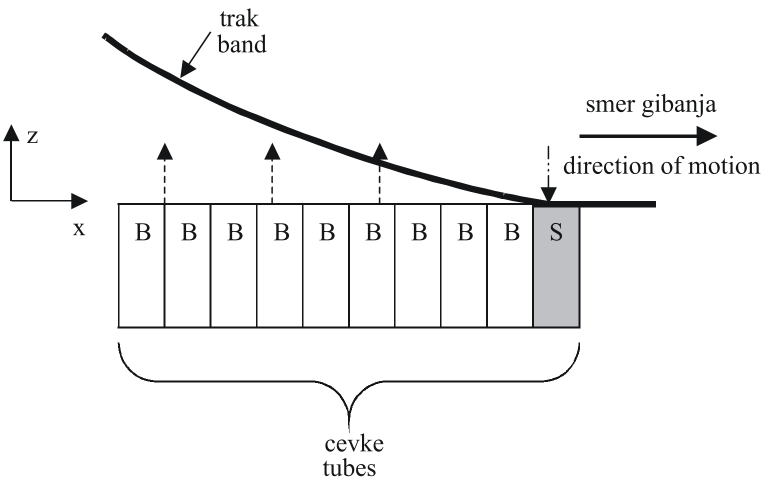
- **Podkorak 2**: Trak je prisesan na NPAP samo na njenem desnem robu, medtem ko je prost drugod. Cevke na desnem navpičnem robu sesajo, medtem ko vse preostale cevke pihajo (slika 4).

V podkoraku 2 se leva stran traku odmakne od NPAP in se upogne navzgor (slika 5), zaradi

the local forces, which are equally distributed over the surface of the band (force field).

- **Substep 2**: the band is held on the PASD only by the right-hand edge, while it is released elsewhere. The tubes on the right vertical edge suck while all the other tubes blow (Fig. 4).

The left-hand side of the band is bent upwards from the PASD (Fig. 5) in substep 2 due to the blowing



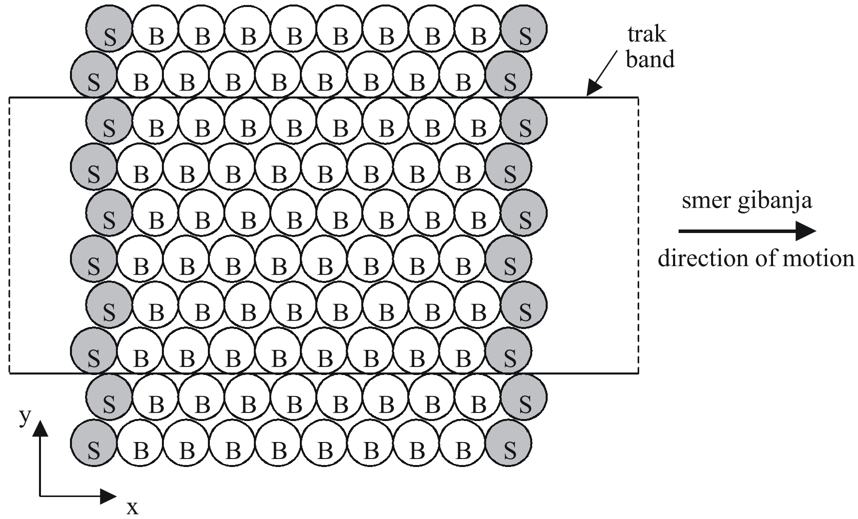
Sl. 5. *Trak se na levi strani upogne navzgor*
Fig. 5. *The band is bent upwards on the left-hand side of the PASD*

pihanja cevk na levi strani in v sredini NPAP. Črtkane črtice na sliki 5 označujejo zračni tok, ki teče iz cevk. Zračni tok povzroči sile na površino traku, ki odmakne trak od površine NPAP in ga upogne.

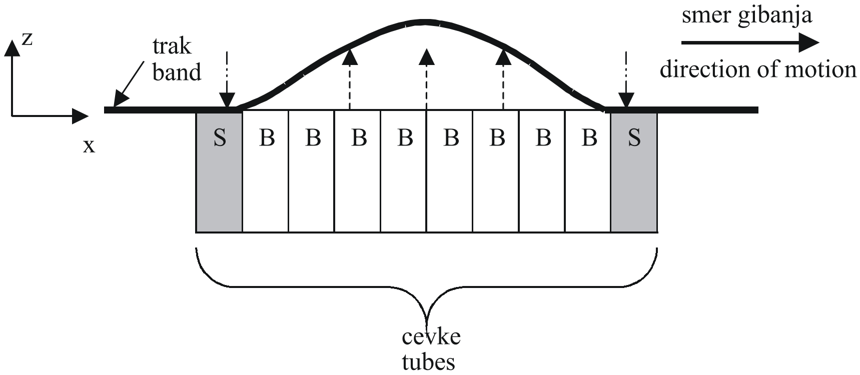
- **Podkorak 3**: Trak je pritisnjen na NPAP na njegovi levi in desni strani in ima obliko hribčka (slika 7) zaradi

action of the tubes on the left-hand side and in the middle of the PASD. The dashed arrows in Figure 5 represent the airflow from the tubes. The air flow produce forces on the surface of the band that lift the band from the surface of the PASD and twist it.

- **Substep 3**: The band is pressed to the PASD on its left-hand and right-hand sides and has the form of a



Sl. 6. *Podkorak 3 za vzdolžno gibanje desno (pogled od zgoraj)*
Fig. 6. *Substep 3 for translational motion right (top view)*



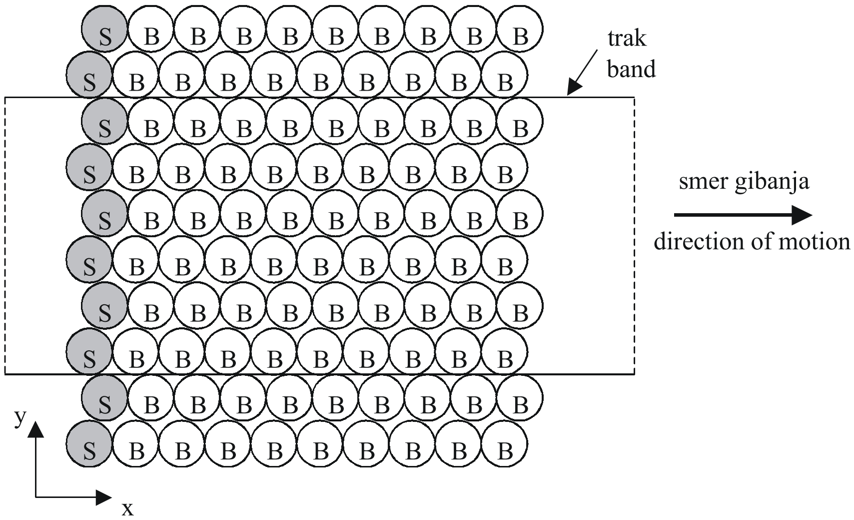
Sl.7. *Trak ima obliko hribčka (stranski pogled)*
Fig. 7. *Band has the form of a hill (side view)*

sesanja cevk na levi in desni strani NPAP in učinka pihanja v sredini (slika 6).

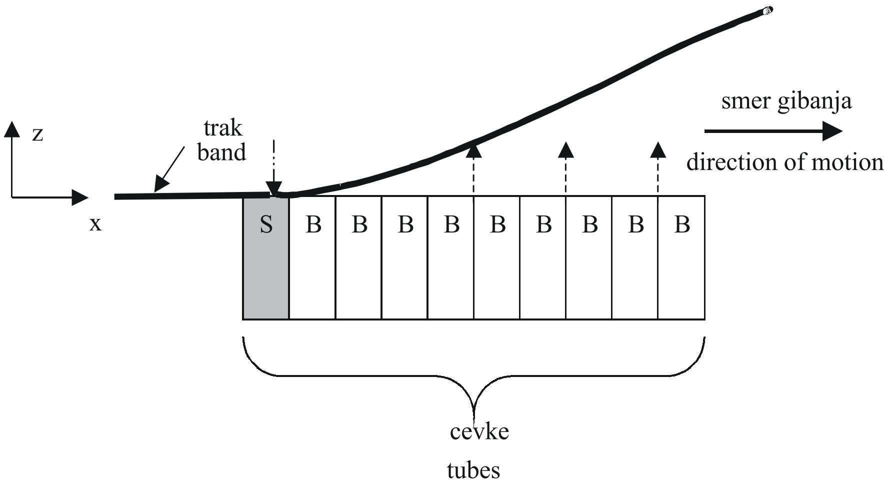
- **Podkorak 4**: Trak je pritisnjen na NPAP na levi strani NPAP in je prost drugod. Cevke na levem robu še sesajo, medtem ko cevke na desni strani NPAP pihajo.

hill (Fig. 7) due to the sucking action on both left-hand and right-hand sides of the PASD and the blowing action in the middle (Fig. 6).

- **Substep 4**: The band is pressed to the PASD on the left-hand edge of the PASD and released elsewhere. The left-hand edge of the PASD remains in suction action, while the tubes on the right-hand edge of the PASD blow.



Sl. 8. *Podkorak 4 za vzdolžno gibanje desno (pogled od zgoraj)*
Fig. 8. *Substep 4 for translational motion right (top view)*



Sl. 9. *Desni rob traku je prost*
Fig. 9. *Right-hand edge of the band is free*

- **Podkorak 5**: Trak se prične premikati na desno, ker se število stolpcev cevk NPAP, ki sesajo na levem vogalu v tem zadnjem koraku, poveča (slika 10).

Trak se prične premikati na desno (slika 11).

Med zaporednim izvajanjem korakov za vzdolžno gibanje podkoraku 5 sledi podkorak 1 iz naslednjega koraka. Če pa se bo gibanje ustavilo, tedaj se za podkorakom 5 izvede samo še podkorak 1, zato da se gibanje konča s trakom, tesno pritisnjenim na NPAP.

Gibanje traku za en korak je predstavljeno na sliki 12.

Dolžina traku v obliki hriba je večja od dolžine ravnega traku (sl.12). Trak naredi med gibanjem hribček in se premakne za razliko dolžin:

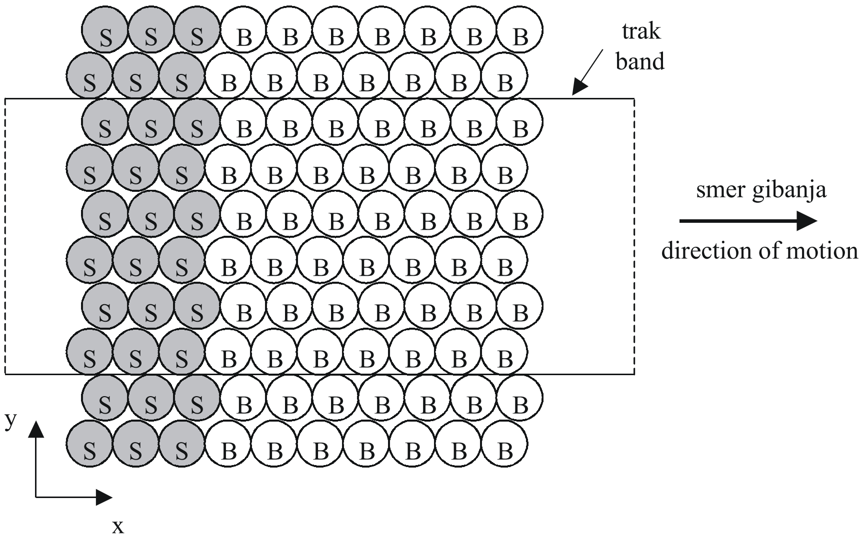
- **Substep 5**: The band is forced to move to the right because the number of columns of the PASD in suction action on its left-hand edge is increased in this last substep (Fig. 10).

The band starts to move to the right (Fig. 11).

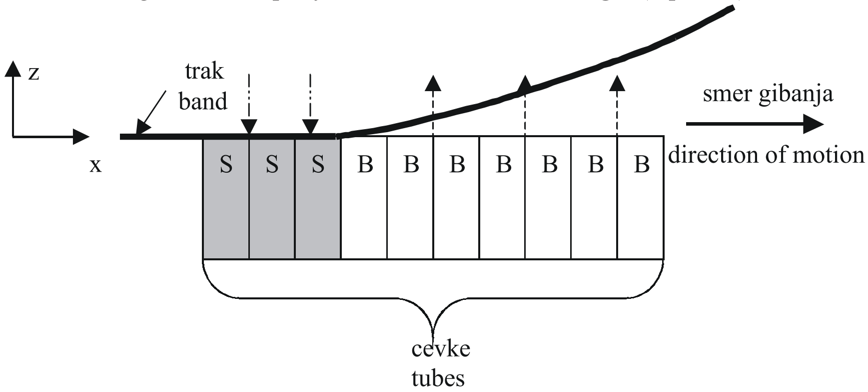
During the sequential execution of steps for translational motion substep 5 is followed by substep 1 of the following step. When the motion is going to stop after substep 5 only substep 1 is executed in order to finish with the band tightly pressed to the PASD.

The translation of the band for one step is represented in Figure 12.

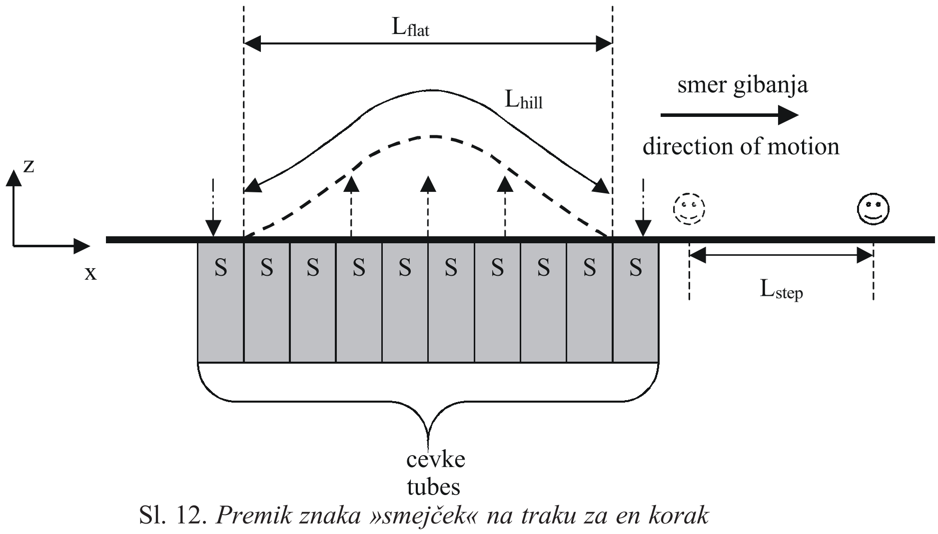
The length of the band in the form of a hill is greater than the length of the flat band (Fig. 12). The band makes a hill during the motion. The band has moved the difference of lengths:



Sl. 10. *Podkorak 5 za vzdolžno gibanje desno (pogled od zgoraj)*
Fig. 10. *Substep 5 for translational motion right (top view)*



Sl. 11. *Trak se premika na desno*
Fig. 11. *Band moves to the right*



Sl. 12. *Premik znaka »smejček« na traku za en korak*
Fig. 12. *Translation of a smile mark on the band for one step*

$$L_{step} = L_{hill} - L_{flat} \qquad (1),$$

ko se razširi prek matrike cevk in se spet zravna.

Dolžina enega vzdolžnega koraka traku je odvisna od sile pihanja, gibljivosti traku in dolžine L_{flat}. Če trak ni dovolj gibčen, ne bo

when the band spreads over the array of tubes again and becomes flat.

The length of one translational step of the band depends on the force of the blow pressure, the flexibility of oblikoval hribčka. Namesto tega se bo trak zravnan prilepil nazaj na površino NPAP (kot togo telo). Najmanjši korak premikanja je določen z razmerjem med gibljivostjo traku in dolžino L_{flat} pri danem tlaku. Sila zaradi pihanja vpliva na dolžino vzdolžnega premika prek povečanja oziroma zmanjšanja višine hribčka, ki se ustvari v tretjem podkoraku vzdolžnega gibanja. Višji kot je pritisk pihanja, daljši bo L_{hill} in zaradi tega bo daljši tudi korak L_{step}. Seveda je zgornja vrednost tlaka pihanja omejena z vrednostjo, pri kateri trak odpihne s površine.

Vzdolžno gibanje nazaj ustvarimo z medsebojno zamenjavo podkorakov 2 in 4 ter ustrezno spremembo podkoraka 5.

Vzolžno gibanje traku lahko ustvarimo tudi za poljubno usmeritev traku na NPAP, ki ni enaka usmeritvi referenčnega koordinatnega sistema. V tem primeru je potrebno dejanska področja cevk sesanja in pihanja za en korak gibanja usmeriti v skladu z dejansko usmeritvijo traku na NPAP. Takšno gibanje smo izvedli in testirali za delitev kota usmeritve 20° do 25°, ki je določen z dejansko konstrukcijo (številom cevk) NPAP in se lahko izboljša s povečanjem števila cevk na NPAP.

1.1.2 Vrtilno gibanje

Vrtilno gibanje traku na NPAP se pojavi le v kombinaciji z vzdolžnim gibanjem. Trak se vrti in premika hkrati. Vrtilno gibanje traku lahko izvedemo ob hkratnem vzdolžnem gibanju naprej ali nazaj.

Referenčni koordinatni sistem je pritrjen na NPAP, lastni koordinatni sistem pa je pritrjen na trak, kakor je opisano v razdelku 1.1.1. Za potrebe definiranja vrtilnega gibanja traku definiramo še en dodaten koordinatni sistem. Os z dodatnega koordinatnega sistema je usmerjena enako kakor os z referenčnega koordinatnega sistema. Izhodišče dodatnega koordinatnega sistema je v sečišču roba traku na zgornji strani traku in navpične vrste cevk, ki sesajo (sl. 16). Po definiciji je vrtilno gibanje desno vrtenje traku okoli osi z dodatnega koordinatnega sistema v smeri urnega kazalca, medtem ko je vrtilno gibanje levo vrtenje traku okoli osi z dodatnega koordinatnega sistema v nasprotni smeri urnega kazalca. Najprej je podrobno opisano vrtilno gibanje desno z gibanjem nazaj. Nato so kratko opisani vrtilno gibanje levo z gibanjem nazaj, vrtilno gibanje levo in desno z gibanjem naprej in vrtilno gibanje levo in desno z drugačno lego osi vrtenja.

the band and the length L_{flat}. If the band is not flexible enough it will not form the hill. The band will stick to the array in the flat form (like a rigid body) instead. The minimum translation step is determined by the ratio between the flexibility of the band and length L_{flat} at a given blow pressure. The force of the blow pressure influences the length of the translational step by increasing or decreasing the height of the hill created in the third substep of the translational motion. The higher the blow pressure the longer L_{hill} will be, and consequently, the longer L_{step} will be. Of course there are limits to how much the blow pressure can be increased without blowing the band off the array.

Translational motion backward is generated by the exchange of substeps 2 and 4 and a suitable modification to substep 5.

The translational motion of the band for the orientation of the band that is not equal to the orientation of the reference coordinate system is implemented so that the actual sucking and blowing zones of one step are oriented in accordance with the actual orientation of the band on the PASD. Such motion was implemented and tested for directions separated in a 20° to 25° raster. This direction raster is given by the actual construction (number of tubes) of the PASD and could be improved by an increased number of the tubes on the PASD.

1.1.2 Rotational Motion

Rotational motion of the band on the PASD appears only in combination with translational motion; the band rotates and translates at the same time. During rotational motion the translational motion forward or backward could be implemented.

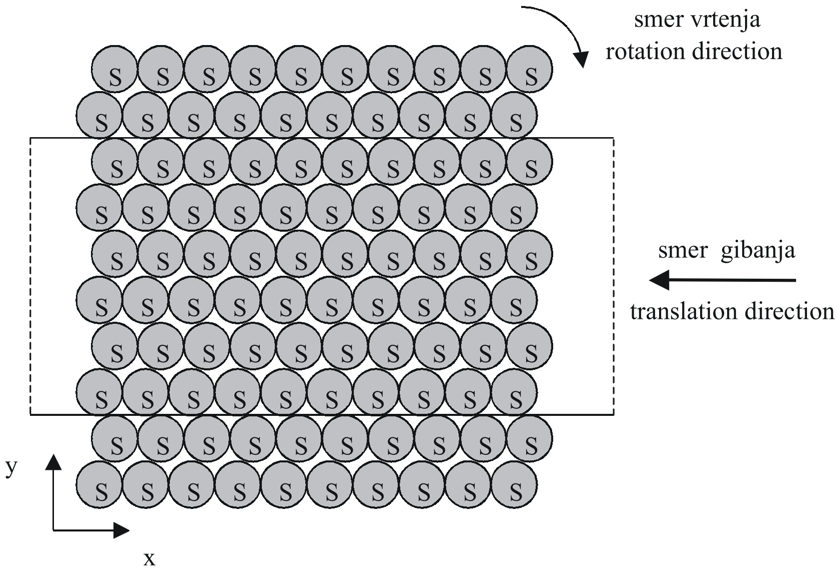
A reference coordinate system is attached to the PASD and the eigen coordinate system is attached to the band as described in section 1.1.1. In order to define rotational motion of the band an additional coordinate system is defined. The z-axis of the additional coordinate system is oriented in the same way as the z-axis of the reference coordinate system. The origin of the additional coordinate system is at the intersection of the band edge on the upper side of the band and the vertical sucking line (see Figure 16). By definition the rotational motion to the right is rotation of the band around the z-axis of the additional coordinate system in a clockwise direction, while rotational motion to the left is rotation of the band around the z-axis of the additional coordinate system in a counter-clockwise direction. First, rotational motion to the right with translation backwards is described in detail. Then, rotational motion to the left with translation backwards, rotational motion to the left and right with translational motion forwards and rotational motion to the left and right with different location of axis of rotation are briefly described.

1.1.2.1 Vrtilno gibanje desno s premikom nazaj

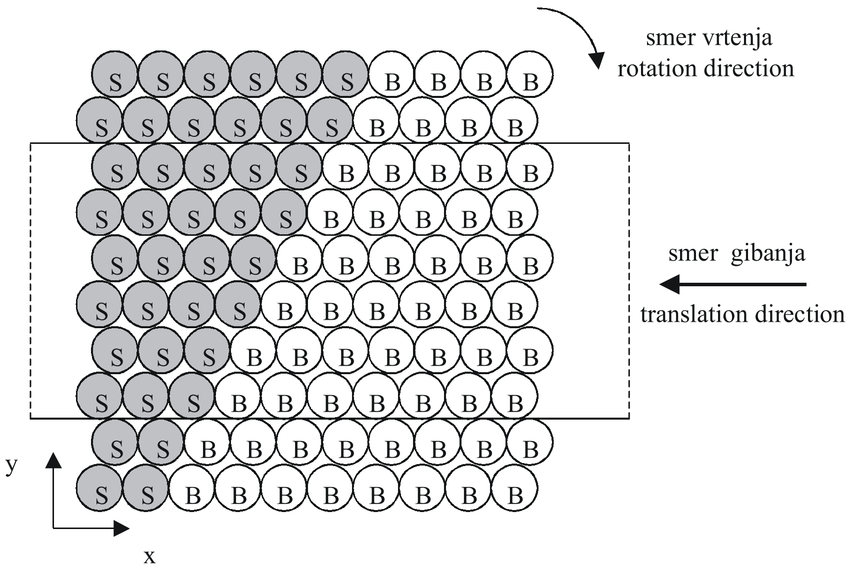
Predstavljeno je zaporedje podkorakov za vrtilno gibanje desno.
- **Podkorak 1**: Vse cevke sesajo in trak je pritisnjen na NPAP (slika 13).
- **Podkorak 2**: Trak je prisesan na NPAP v levem zgornjem vogalu in prost drugod. Cevke NPAP sesajo zrak v levem zgornjem kotu, medtem ko vse druge cevke pihajo zrak (sl. 14). Zato se trak dvigne na desni strani (sl. 15), vendar se trak ne dvigne na obeh straneh enako, ker ima levo področje cevk, ki sesajo, nagib proti vodoravnemu robu NPAP.
- **Podkorak 3**: Cevke na desni v navpični vrstici pričnejo sesati, tako da hkrati sesata dve področji

1.1.2.1. Rotational motion to the right with translation backwards

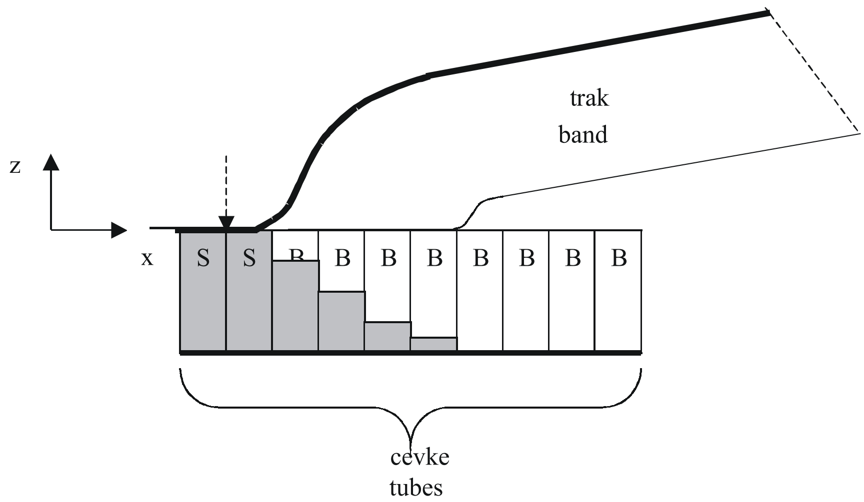
A sequence of substeps for one step of the rotational motion to the right is represented.
- **Substep 1**: Initially, all the tubes are sucking and the band is pressed to the PASD (Fig. 13).
- **Substep 2**: The band is pressed to the PASD at the left-hand upper corner and released elsewhere. The left-hand upper corner is in sucking action while the remainder of the PASD is in blowing action (Fig. 14). As a result, the band is lifted on the right-hand side (Fig. 15) but this lift is not equal on both sides of the band because the left sucking zone has an inclination towards the horizontal edge of the PASD.
- **Substep 3**: The right vertical sucking line appears, so there is a sucking zone on both sides of the array



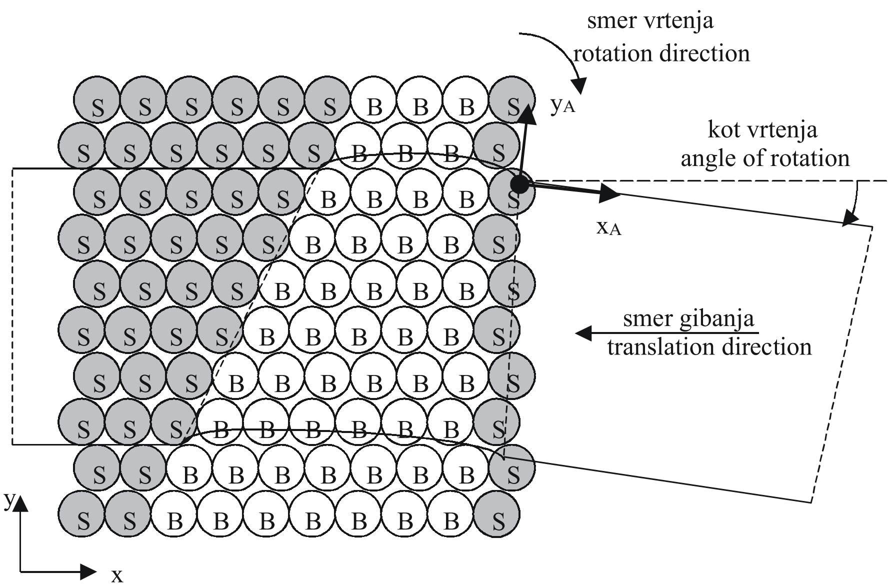
Sl. 13. *Podkorak 1 za vrtilno gibanje (pogled od zgoraj)*
Fig. 13. *Substep 1 for rotational motion (top view)*



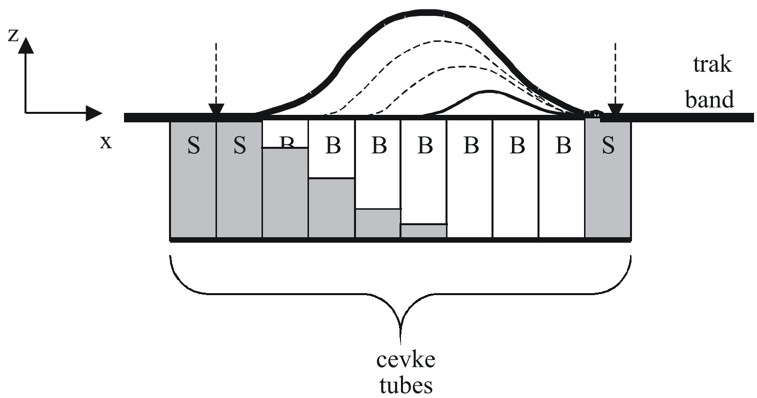
Sl. 14. *Podkorak 2 vrtilnega gibanja desno*
Fig. 14. *Substep 2 of rotational motion to the right*



Sl. 15. *Trak je dvignjen na desni strani*
Fig. 15. *The band is lifted on the right-hand side*



Sl. 16. *Podkorak 3 za vrtilno gibanje desno z gibanjem nazaj*
Fig. 16. *Substep 3 for rotational motion to the right with translation backward*



Sl. 17. *Hribček traku v podkoraku 3*
Fig. 17. *A hill of the band is created in substep 3*

cevk - na vsaki strani matrike eno področje cevk (slika 16) in trak se zvije v obliko hribčka (slika 17). Dolžina hribčka ni enaka na obeh straneh traku. Razlika med dolžino hribčka na obeh straneh povzroča vrtenje traku. Os vrtenja je definirana glede na koordinatno izhodišče dodatnega koordinatnega sistema.

- **Podkorak 4**: Sesa samo področje cevk na desni – desni navpični rob (slika 18), medtem ko je trak na levi strani prost in vse področje cevk na levi piha (slika 19).
- **Podkorak 5**: Področje sesanja na desni strani NPAP se razširi (sl. 20), zato se trak prične premikati nazaj (slika 21).

Podkoraku 5 sledi podkorak 1 naslednjega koraka (slika 22).

1.1.2.2 Vrtilno gibanje levo s premikom nazaj

Vrtilno gibanje levo s premikom nazaj se razlikuje od vrtilnega gibanja desno s premikom

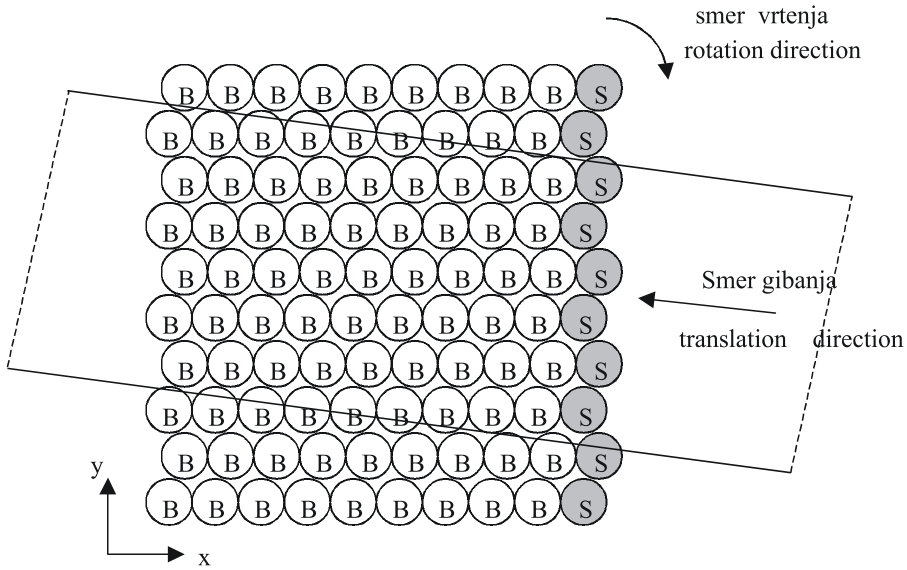
(Fig. 16) and the band makes a hill (Fig. 17). The length of the hill is not equal on both sides of the band. The difference between the length of the hill on both sides of the band creates a rotation of the band. The axis of rotation is defined with respect to the origin of the additional coordinate system.

- **Substep 4**: Only the right-hand sucking zone (edge) remains in a sucking action (Fig. 18) and the left-hand side of the band is released due to the blowing action of all the other tubes (Fig. 19).
- **Substep 5**: More sucking action is applied to the right-hand side of the PASD (Fig. 20) and the band is forced to move backwards (Fig. 21).

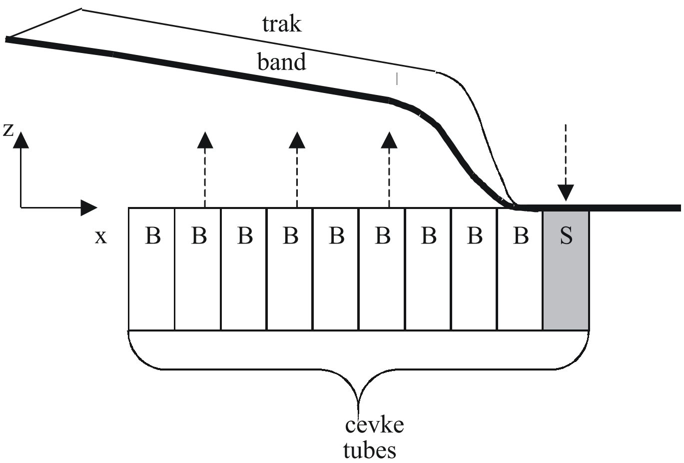
Substep 5 is followed by substep 1 of the next step (Fig. 22).

1.1.2.2 Rotational motion to the left with translation backwards

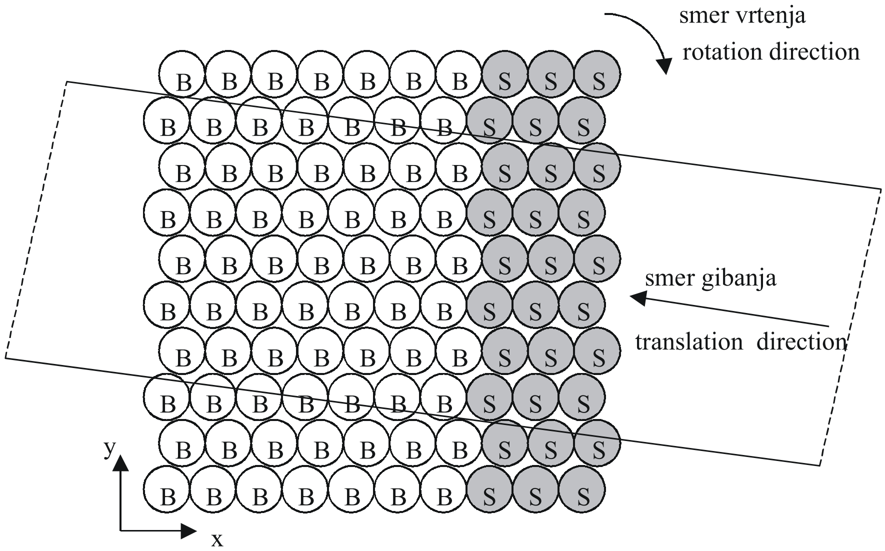
Rotational motion to the left with translation backwards is different from the rotational motion to



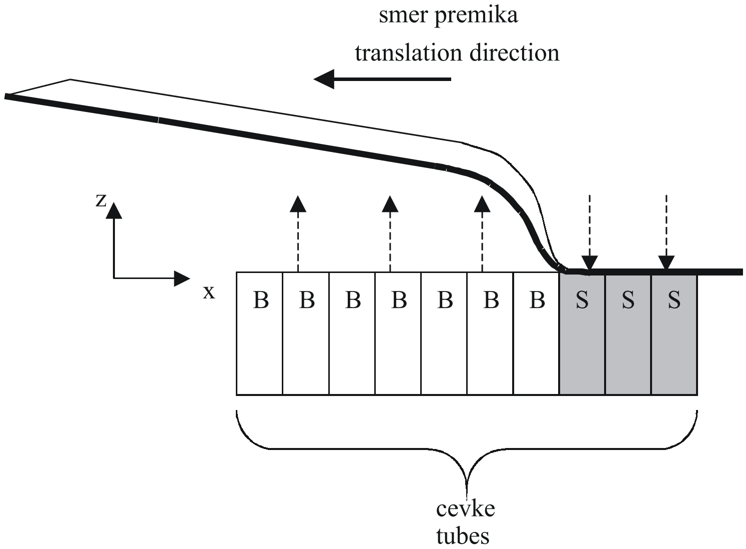
Sl. 18. *Podkorak 4 za vrtilno gibanje desno*
Fig. 18. *Substep 4 for rotational motion to the right*



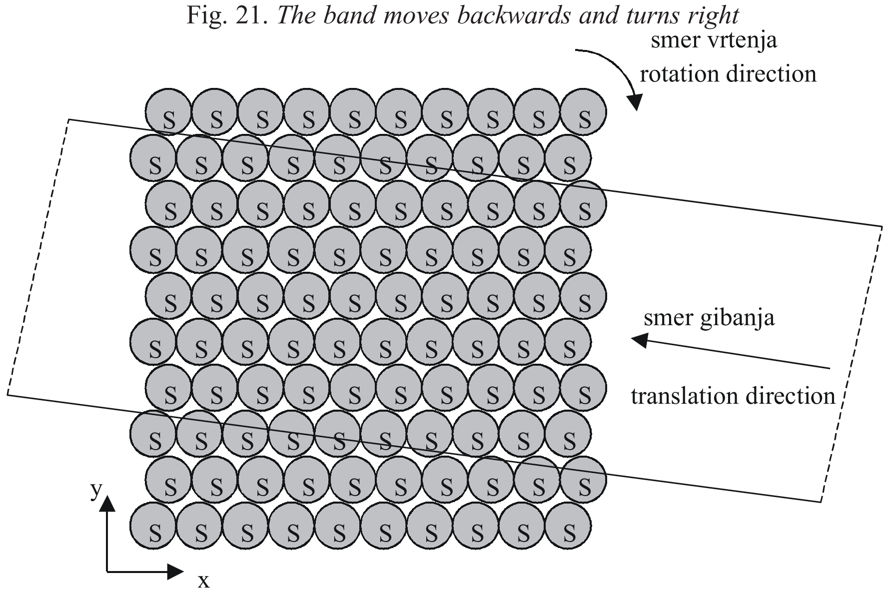
Sl. 19. *Trak je dvignjen na levi strani NPAP*
Fig. 19. *The band is lifted on the left-hand side of the PASD*



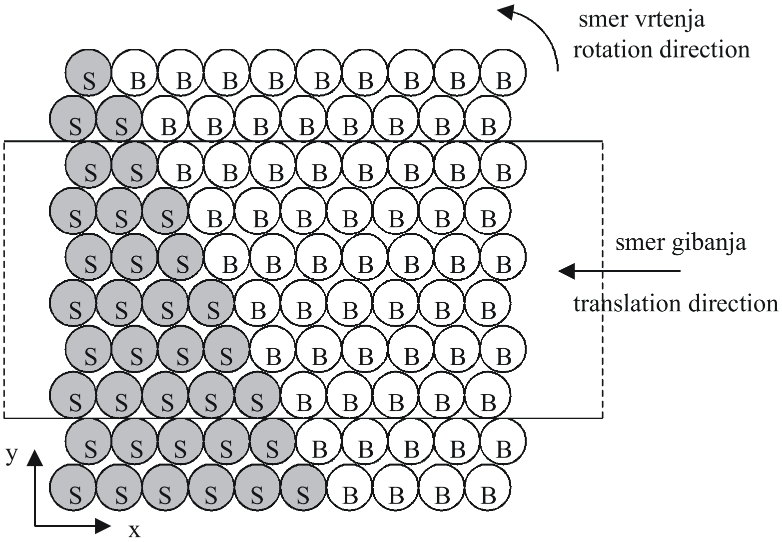
Sl. 20. *Podkorak 5 za vrtilno gibanje desno*
Fig. 20. *Substep 5 for rotational motion to the right*



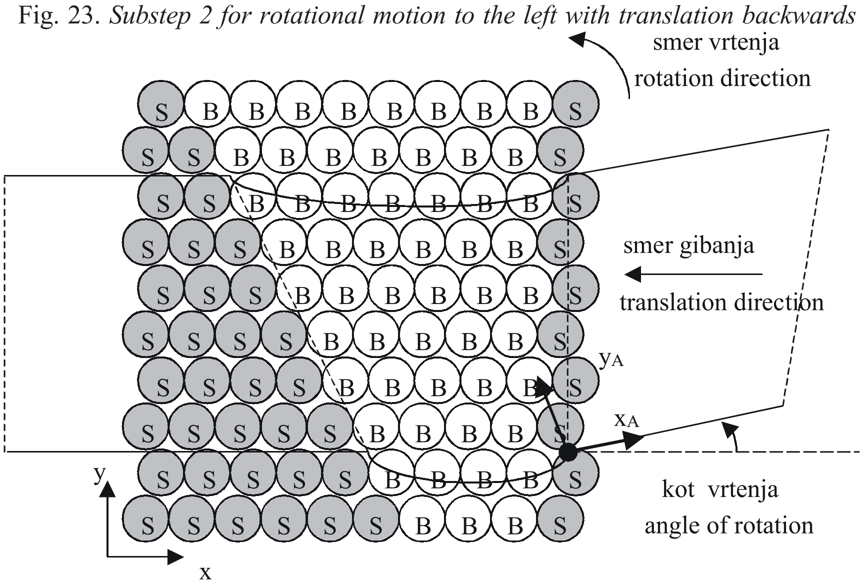
Sl. 21. *Trak se premika nazaj in suče desno*
Fig. 21. *The band moves backwards and turns right*



Sl. 22. *Podkorak 1 naslednjega koraka vrtenja traku*
Fig. 22. *Substep 1 in the following step of rotation*



Sl. 23. *Podkorak 2 za vrtilno gibanje levo s premikom nazaj*
Fig. 23. *Substep 2 for rotational motion to the left with translation backwards*



Sl. 24. *Podkorak 3 za vrtilno gibanje levo s premikom nazaj*
Fig. 24. *Substep 3 for rotational motion to the left with translation backwards*

nazaj samo po obliki levega področja sesanja cevk, ki se pojavi v podkorakih 2 in 3, znotraj zaporedja podkorakov. Podkorak 2 za vrtilno gibanje levo s premikom nazaj je prikazan na sliki 23.

1.1.2.3 Vrtilno gibanje levo in desno s premikom naprej

Vrtilno gibanje levo oziroma desno s premikom naprej lahko obravnavamo kot modificirano vrtilno gibanje levo oziroma desno s premikom nazaj. Glavna razlika med obema postopkoma je v zaporedju, v katerem izvajamo levo področje sesanja in desno navpično področje sesanja. V nadaljevanju je prikazano le zaporedje podkorakov za vrtilno gibanje desno s premikom naprej. Zaporedje podkorakov za vrtenje levo s premikom naprej je zgrajeno podobno kakor vrtenje desno s premikom naprej (glej razdelek 1.1.2.2).

the right with translation backward only in the inclination of the left-hand sucking zone, which appears in substeps 2 and 3 of the sequence for one step. Substeps 2 and 3 for rotational motion to the left with translation backwards are represented in Figures 23 and 24.

1.1.2.3. Rotational motion to the left and to the right with translation forwards

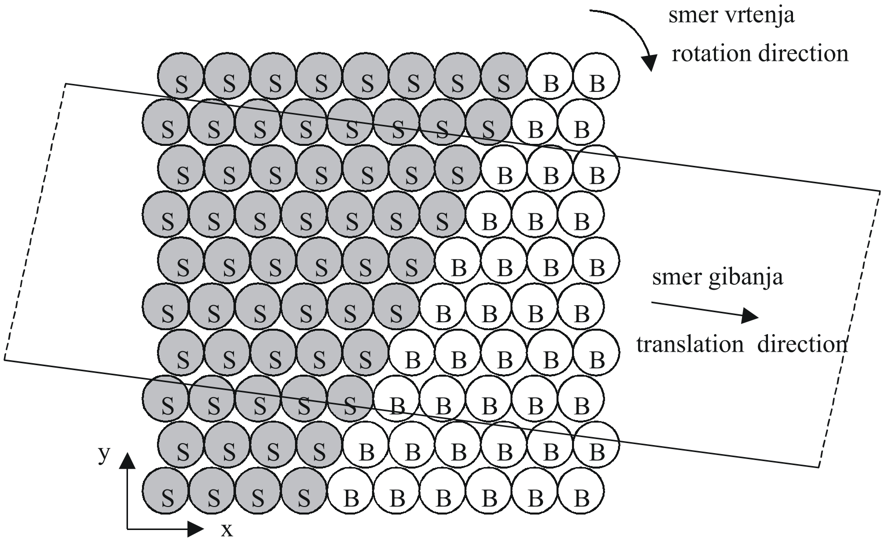
Rotational motion to the left/right with translation forwards could be considered as a modification of rotational motion to the left/right with translation backwards. The main difference between the two approaches is in the sequence in which the left-hand inclined sucking zone and the right-hand vertical sucking zone are applied. Only the sequence of substeps for rotation to the left with translational motion forwards is discussed in the following. The sequence of substeps for rotation to the left with translational motion forwards is built similar to the rotation to the right (see section 1.1.2.2).

Zaporedje podkorakov za vrtenje desno s premikom naprej je:
- podkorak 1 je enak podkoraku 1 za vrtenje desno s premikom nazaj (sl. 13),
- podkorak 2 je enak podkoraku 4 za vrtenje desno s premikom nazaj (sl. 18, 19),
- podkorak 3 je enak podkoraku 3 za vrtenje desno s premikom nazaj (sl. 16, 17),
- podkorak 4 je enak podkoraku 2 za vrtenje desno s premikom nazaj (sl. 14 in 15),
- podkorak 5: levo področje sesanja se razširi za dve dodatni vrstici (sl. 25, 26)

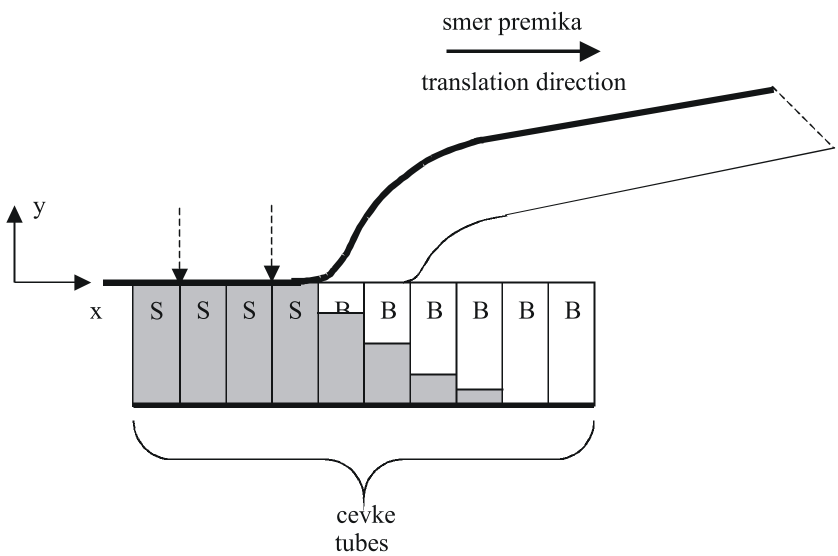
Dve dodatni vrstici sesanja na levi sprožita premikanje traku na desno.

The sequence of substeps for rotation to the right with translational motion forwards are:
- substep 1 is equal to the substep 1 for rotation to the right with translational motion backwards (Fig. 13),
- substep 2 is equal to the substep 4 for rotation to the right with translational motion backwards (Figs. 18, 19),
- substep 3 is equal to the substep 3 for rotation to the right with translational motion backwards (Figs. 16, 17),
- substep 4 is equal to the substep 2 for rotation to the right with translational motion backwards (Figs. 14, 15),
- substep 5: two additional sucking lines are added to the inclined sucking zone (see Figures 25, 26).

Two additional sucking lines on the left force the band to move to the right.



Sl. 25. *Podkorak 5 za vrtenje desno s premikom naprej*
Fig. 25. *Substep 5 for rotation to the right with translational motion forwards*



Sl. 26. *Trak se vrti desno in premika naprej*
Fig. 26. *The band rotates and translates forwards*

1.1.2.4 Vrtilno gibanje desno in levo z drugačnimi legami vrtilne osi

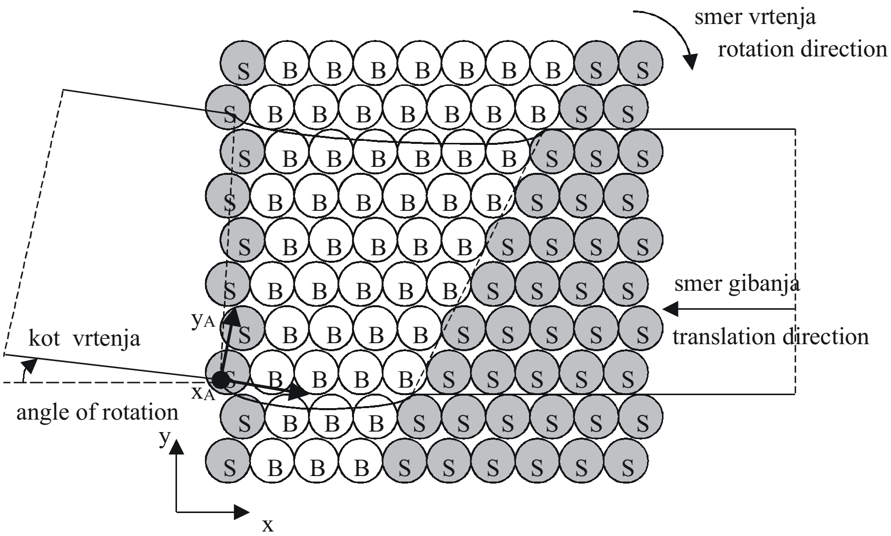
Vrtilna gibanja, opisana v prejšnjih razdelkih lahko izvedemo tudi z drugačno lego vrtilne osi. Dejanska lega vrtilne osi je podana z dodatnim koordinatnim sistemom. Sprememba lege vrtilne osi je posledica vrtenja karakterističnega vzorca pihanja in sesanja cevk na NPAP. Vrtenje karakterističnega vzorca pihanja in sesanja za 180° določa novo dodatno lego vrtilne osi za vrtilno gibanje desno s premikom nazaj (podkorak 3). Dodatna lega vrtilne osi za vrtilno gibanje desno s premikom nazaj je predstavljena na sliki 27.

Z vrtenjem karakterističnega vzorca pihanja in sesanja za 180° dobimo dodatno lego vrtilne osi za vrtilno gibanje levo s premikom nazaj (podkorak 3). Dodatna lega vrtilne osi za vrtilno gibanje levo s premikom nazaj je predstavljena na sliki 28.

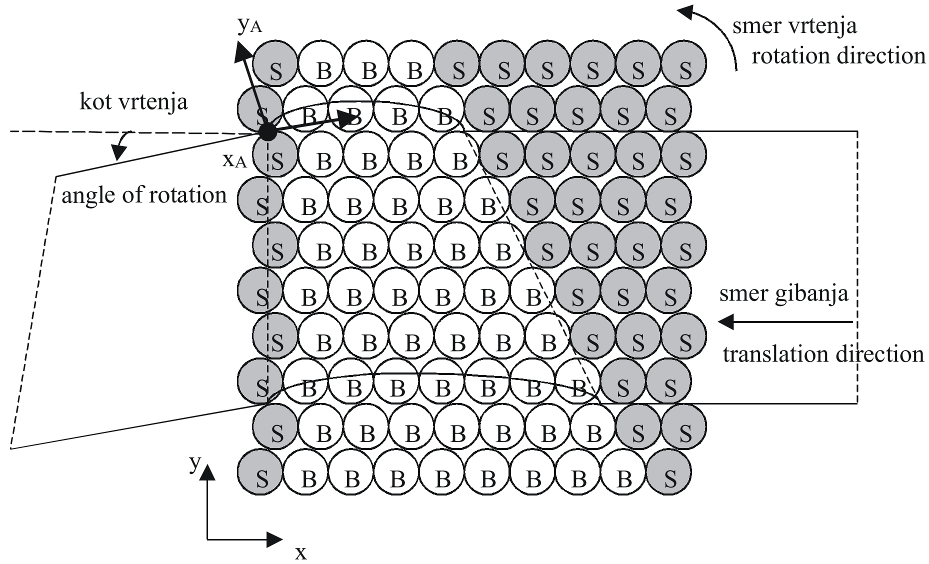
1.1.2.4 Rotational motion to the right and to the left with other locations of the rotation axis

The rotational motions described in the previous sections could also be implemented with other locations of the rotation axis. The actual location of the rotation axis is given by the additional coordinate system. A change in the location of the rotation axis is a result of a rotation of a characteristic pattern of blowing and sucking action on the PASD. A rotation of the characteristic pattern of blowing and sucking action for 180° gives a new location of the rotation axis for rotational motion to the right with translation backwards (substep 3) represented in Figure 27.

With a rotation of a characteristic pattern of blowing and sucking action for 180° another location of the rotation axis for rotational motion to the left with translation backwards (substep 3) is obtained. It is represented in Figure 28.



Sl. 27. *Dodatna lega vrtilne osi za vrtenje desno s premikom nazaj*
Fig. 27. *Another location of rotation axis for rotation to the right with translation backwards*



Sl. 28. *Dodatna lega vrtilne osi za vrtenje levo s premikom nazaj*
Fig. 28. *Another location of the rotation axis for rotation to the left with translation backwards*

1.1.3 Premikanje na temelju vrtilnega gibanja

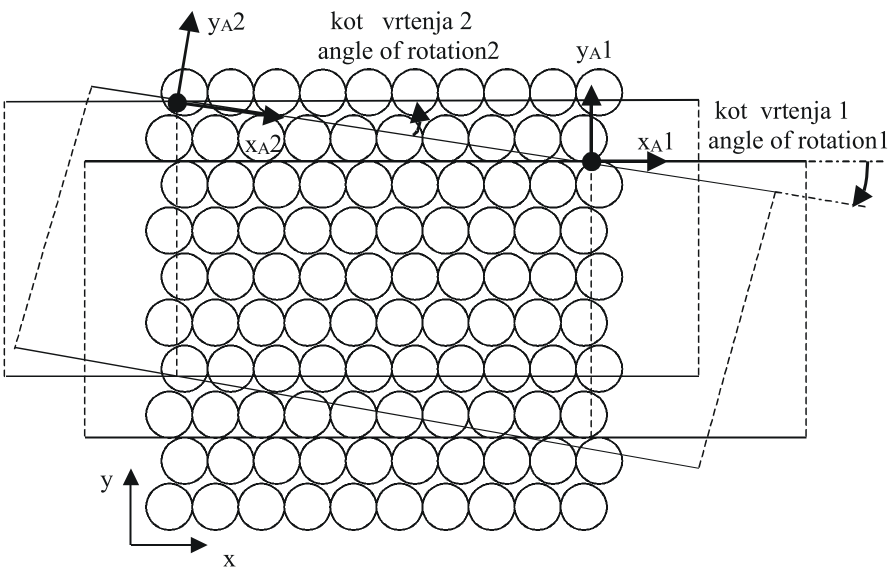
Poleg gibanja traku vzdolž dolžine traku je mogoče gibanje traku izvesti tudi s pomočjo dveh zaporednih vrtenj okoli različnih osi vrtenja. Gibanje vzdolž osi y referenčnega koordinatnega sistema se pojavi (sl. 29), če vrtilnemu gibanju desno s premikom nazaj in vrtiščem na desni strani NPAP (sl. 16) sledi vrtilno gibanje levo s premikom nazaj in vrtiščem na levi strani NPAP (sl. 28).

Vzdolžno gibanje na temelju vrtenj je gibanje pravokotno na gibanje vzdolž dolžine traku, je pravzaprav gibanje vzdolž širine traku. Zato lahko trak premikamo vzdolžno z dvema prostostnima stopnjama v ravnini. V primeru vzolžnega gibanja na temelju vrtenj se trak giblje vzdolž dolžine in širine traku hkrati.

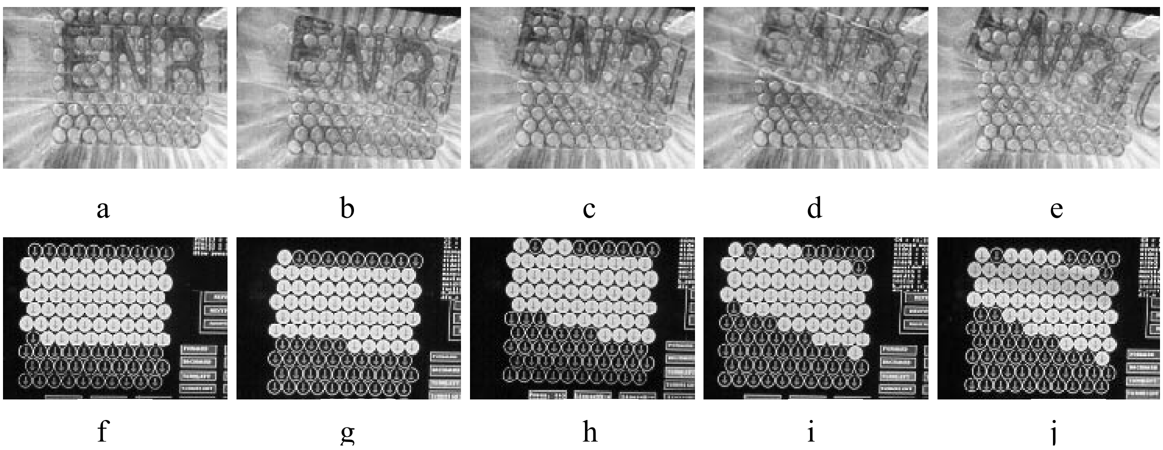
1.1.3 Translational Motion Based on Rotational Motion

Besides the translational motion along the length of the band the translational motion of the band is achieved by a subsequent implementation of two rotational motions around a different axis of rotation. Translational motion along the y-axis of the reference coordinate system appears (see Figure 29) if rotational motion to the right with translation backwards and rotation axis on the right-hand side of PASD (Figure 16) is followed by rotational motion to the left with translation backwards and the rotation axis on the left-hand side of the PASD (Figure 28).

Translational motion based on rotational motion is a motion perpendicular to the translational motion along the length of the band, i.e. translational motion along the width of the band. Therefore, the band could move translationally with two degrees of freedom in the plane. The band moves along the length and the width of the band at the same time during translational motion based on rotational motion.



Sl. 29. *Premik traku na temelju vrtenj*
Fig. 29. *Translation of the band based on rotations*



Sl. 30. *Vrtenje traku desno med izvajanjem na NPAP in zaznavanje traku*
Fig. 30. *Actual rotation of the band to the right performed on the PASD with the band's detection*

1.1.4 Eksperimentalni rezultati in povzetek

Zgornja vrsta slik na sliki 30 prikazuje izvedbo mnogih korakov vrtenja traku desno na NPAP. Spodnja vrsta slik na sliki 30 pa prikazuje zaznavanje traku na NPAP v istih časovnih trenutkih, kakor so prikazani v zgornji vrsti slik.

Preskusi krmiljenja gibanja brez povratne zveze na NPAP so pokazali, da se med gibanjem objekta pogosto pojavijo motnje. Te motnje povzročijo neželena odstopanja gibanja traku.

Preskusi so pokazali, da je zelo verjetno, da se trak med vzdolžnim gibanjem tudi zasuče. Najbolj verjetna razlaga za to je, da dolžina koraka traku ni enaka na zgornjem in spodnjem robu traku. Podobno je zelo verjetno, da se bo trak premikal med vrtilnim gibanjem, ker je os vrtenja, zaradi motenj, malo prestavila svojo lego. Motnje so lahko tudi posledica sprememb v zračnem tlaku, ki povzroča pihanje oziroma sesanje zraka, majhnih sprememb gibljivosti traku, ločljivosti NPAP itd. Zato so potrebne (na osnovi povratne zveze) tehnike krmiljenja s povratno zvezo za izvedbo želenega gibanja gibljivega objekta na NPAP.

1.2 Krmiljenje gibanja s povratno zvezo

Tehnike krmiljenja s povratno zvezo temeljijo na povratni vezavi in za njihovo izvedbo je potrebna povratna informacija o gibanju traku. Za opazovanje gibanja predmeta na NPAP so mogoči različni postopki. Ena od možnosti je uporaba sistema videnja na podlagi kamere, druga možnost pa je uporaba vgrajenih zaznaval tlaka za določanje predmeta na NPAP. Mi smo izbrali zaznavanje gibanja predmeta na NPAP na temelju vgrajenih zaznaval tlaka.

Trenutni pogoji, pri katerih izvajamo gibanje traku na NPAP, so takšni, da je dolžina traku, ki ga premikamo bistveno daljša od izmere NPAP v smeri x in y. Zato koncev traku ne moremo zaznati z uporabo vgrajenih zaznaval tlaka. Ker na trakovih ni posebnih oznak po dolžini traku, ne moremo zaznavati premikanja traku po dolžini in zato tudi nismo izvedli krmiljenja za gibanje po dolžini traku s povratno zvezo. Preskusi gibanja brez povratne zveze so pokazali, da se zaradi motenj med gibanjem vzdolž dolžine traku pojavi neželeno vrtenje traku. Zato je zaželena izvedba krmiljenja usmeritve traku s povratno zvezo v kombinaciji premikov vzdolž dolžine traku brez povratne zveze. Za izvedbo želenega krmiljanja je potrebna povratna informacija o usmeritvi traku, ki jo nato uporabimo za kompenzacijo neželene zavrtitve traku med gibanjem vzdolž dolžine traku. Rezultati so prikazani v naslednjih razdelkih.

Za izvedbo kompenzacije neželenih vrtenj med gibanjem vzdolž dolžine traku je potrebna izvedba

1.1.4 Experimental Results and Summary

In the upper row of Figure 30 several steps of actual band rotation to the right on the PASD are shown. In the lower row of Figure 30 the band detection for the same time instants as in the upper row of Figure 30 are shown.

Experiments on open-loop control of motion on the PASD have shown that disturbances frequently occur during the motion of an object. These disturbances cause undesired deviations of the path.

For instance, experiments have shown that the band is very likely to rotate during the translation motion. The most likely explanation for this is that the length of the step on the lower and the upper side of the band is not the same due to disturbances. Similarly, the band is very likely to translate during rotation because the rotation axis moved slightly due to disturbances. The disturbances are a result of variations in the sucking and blowing pressure, a slight variation in the flexibility of the band, the resolution of the PASD, etc. Therefore, closed-loop control techniques (feedback based) are needed to achieve the desired motion of the flexible object on the PASD.

1.2 Closed-Loop Control of Motion

Closed-loop control techniques are feedback based and in order to implement them feedback information about the motion of the band is required. Different approaches are possible for observing the object motion on the PASD. One possibility is to use a camera-based vision system. Another possibility is to use built-in pressure sensors [13] to detect the object on the PASD. We chose built-in pressure sensors to detect the motion of the object on the PASD.

The current conditions for the motion of a band on the PASD are such that the band in motion is much longer than the x and y dimensions of the PASD. Therefore the ends of the band could not be detected by the built-in pressure sensors. Only a part of the longer sides of the band that is on the PASD could be detected. Since no special marks along the length of the band are used, the motion of the band along its length could not be detected and therefore no closed-loop control was implemented for the motion of the band along the length of the band. But the open-loop control experiments have shown that due to disturbances during translational motion along the length of the band, undesired rotation of the band often takes place. Therefore, closed-loop control of the band orientation in combination with open-loop translation along the length of the band is desirable. So, feedback information relating to the band's orientation was used to compensate for the undesired rotation of the band during translational motion along the length of the band. The results are presented in the next subsections.

Detection of the band's orientation on the PASD is needed for the implementation of the comzaznavanja usmeritve traku na NPAP. Zaznavanje trenutne lege in usmeritve traku na NPAP na osnovi zaznaval tlaka NPAP smo izvedli s preprostim algoritmom.

1.2.1 Zaznavanje lege in usmeritve traku

Zaznavanje lege in usmeritve traku je izvedeno ob predpostavki, da je dolžina traku daljša od širine in dolžine matrike cevk in da trak leži prek vse NPAP. Z namenom, da zaznamo lego in usmeritev traku, najprej poiščemo točke, kjer trak seka stranice NPAP. Te točke imenujemo vogali traku. Vogale traku iščemo le v robnih vrsticah na vseh štirih straneh NPAP in jih najdemo na podlagi spremembe stanja cevk (pokrita - nepokrita). Primer zaznavanja vogalov je predstavljen na sliki 31. Vogale imenujemo v enakem zaporedju, kakor jih najdemo, npr: C1, C2, C3. Največje število vogalov je postavljeno na 16. Število najdenih vogalov je večje od 4, če motnje pri meritvi tlaka povzročijo, da se hitro spreminjajo stanja posameznih cevk (bliskanje cevk na zaslonu računalnika) ali če zaznavanje stanja cevk (pokrito - nepokrito) posameznih cevk ni pravilno. V takšnih primerih se stanje omenjenih posameznih cevk oceni na podlagi logične funkcije in stanj sosednjih cevk.

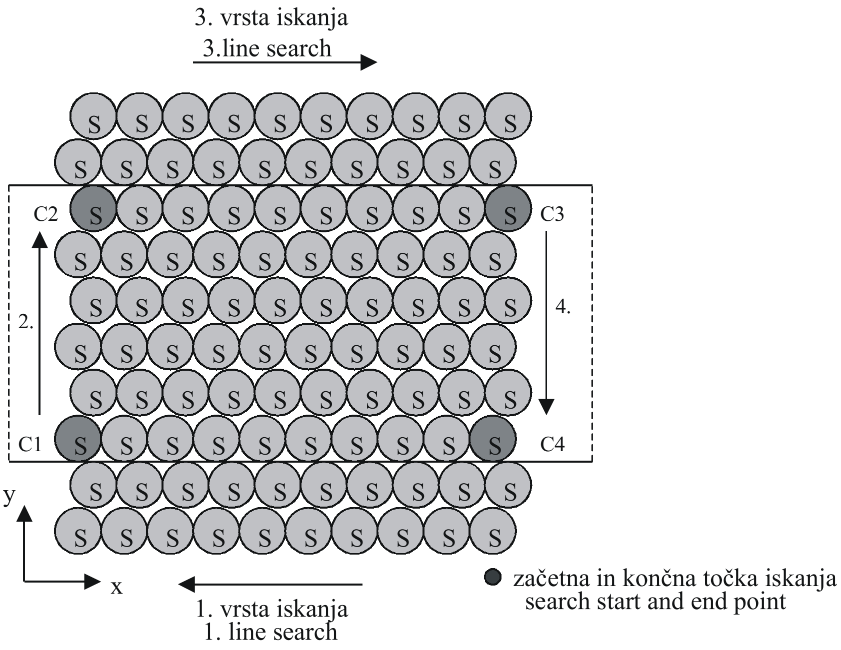
Med iskanjem vogalov se le ti štejejo v vsaki iskalni vrsti posebej. Če je lega traku takšna, da je najdenih manj ko 4 vogalov, tedaj se preveri, kateri vogali so pokriti s trakom. Po tej informaciji se dodajo manjkajoči vogali. Primer je prikazan na sliki 32.

pensation of undesired rotations during translational motion of the band. Therefore, a simple algorithm for detecting the position and orientation of the band with pressure sensors of the PASD was implemented.

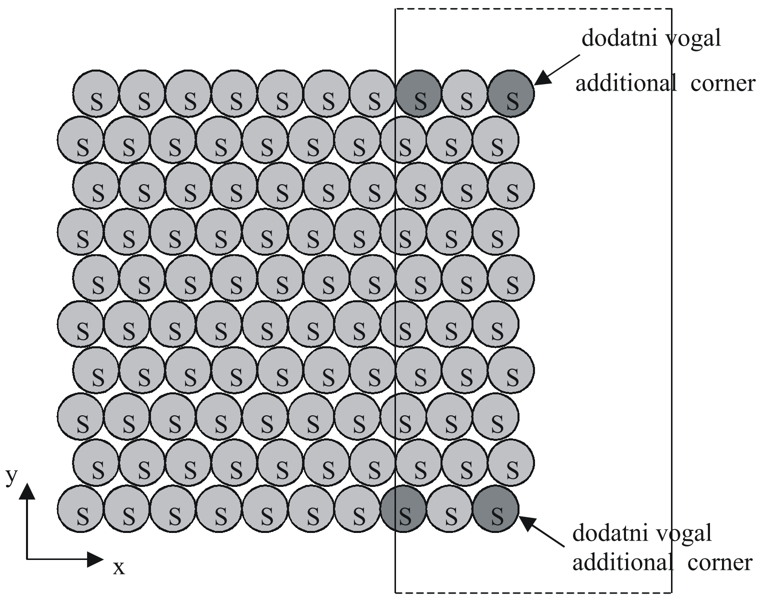
1.2.1 Detection of the position and orientation of the band

Position and orientation detection of the band is implemented assuming that the length of the band is longer than the width or the length of the array and that the band lies across the whole PASD. In order to detect the position and orientation of the band the points where the band intersects the sides of the PASD are first found. These points are called the corners of the band. The corners are searched only in the edge lines on all four sides of the PASD and are found on the basis of the change of the state (covered or uncovered) of the tubes. An example of corner detection is presented in Figure 31. Corners are always named in the same sequence as they are found, for instance: C1, C2, C3. The maximum number of corners is set to 16. A number of corners greater than four can be found when disturbances in the measurement of the pressure cause the detected states of the singular tubes to change rapidly (on the screen some tubes are flashing) and when the detection of the state (covered or uncovered) of the isolated tubes is not correct. In such cases the state of these isolated tubes is estimated with a logical and function of the states of the neighboring tubes.

During the search the corners are counted on each search line separately as well as the total sum of the corners. If the position of the band is such that less than four corners are found, then which of the corners are covered is checked. On the basis of this information the missing corners are added. An example is shown in Figure 32.



Sl. 31. *Zaznani vogali traku in iskalne vrste*
Fig. 31. *Detected corners of the band and the search lines*

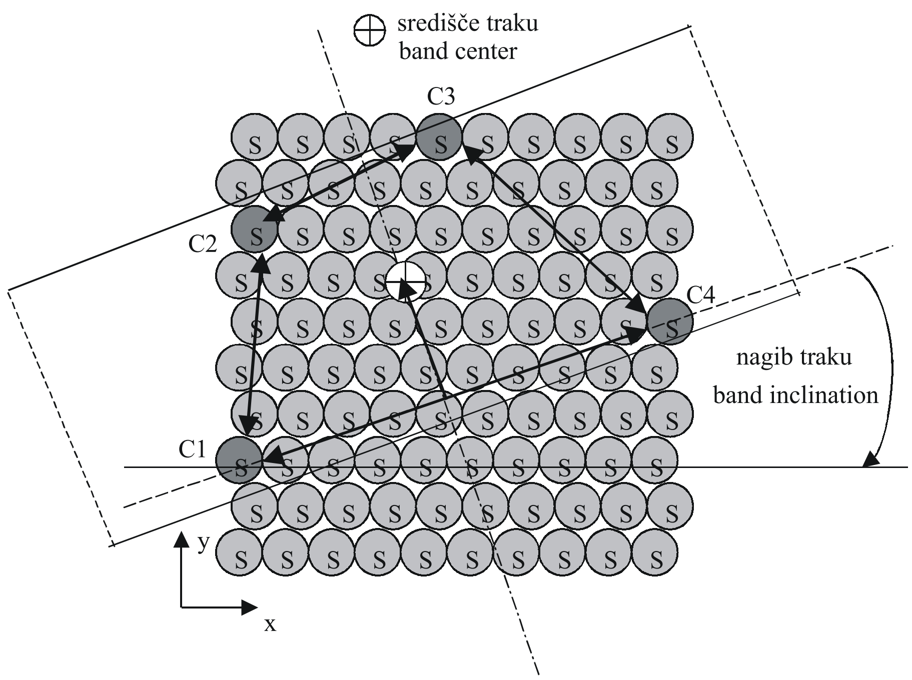


Sl. 32. *Primer dodanih vogalov*
Fig. 32. *An example of added corners*

Na podlagi 4 poiskanih vogalov se izračunajo stranice četverokotnika. Stranica z največjo dolžino se uporabi za izračun nagiba traku. Takšno oceno nagiba traku lahko uporabimo pod predpostavko, da je širina traku približno enako dolga po vsej dolžini traku. Ob sedanji konstrukciji in številu cevk NPAP je najmanjša ločljivost, s katero lahko določamo nagib traku α, ocenjena z enačbo

On the basis of four found corners the sides of the quadrilateral are calculated. The side with the maximum length is used for the calculation of the inclination of the band. Such an estimation of the band inclination could be used assuming that the width of the band is approximately equal along its length. With the present construction and the number of tubes of the PASD [13] a minimum resolution for the determination of band inclination α is estimated with the equation:

$$tg\alpha = \frac{1}{9} = 0{,}11\dot{1} \Rightarrow \alpha = 0{,}11 \quad [rad] \qquad (2).$$



Sl. 33. *Primer določitve središča in nagiba traku*
Fig. 33. *An example of a band center and a band-inclination determination*

Poleg nagiba traku ocenimo na podlagi 4 poiskanih vogalov tudi središče traku. Različne lege traku na NPAP določajo 4 različne oblike likov (pravokotnik, trapez, trapezoid, itn.). Primer lege traku na NPAP, ki tvori trapezno obliko lika, je prikazan na sliki 33. Središče traku je ocenjeno na podlagi stranice z največjo dolžino (med vogaloma C1 in C4) in njej levo (stranica med C1 in C2) ter njej desno (stranica med C4 in C3) sosednjo stranico. Nato izračunamo povprečno vrednost projekcij leve in desne najdaljši sosednje stranice na premico, pravokotno na stranico z največjo dolžino. Središče traku je določeno kot točka, ki leži na polovici povprečne vrednosti projekcij leve in desne sosednje stranice in stranice, ki je pravokotna na stranico z najdaljšo dolžino ter na sredini seka stranico z najdaljšo dolžino.

Če pa je število najdenih vogalov večje od 4, tedaj se ponovi iskanje vogalov. V primeru, da ne najdemo štirih vogalov niti v drugem iskanju, tedaj se iskalni postopek ustavi.

Probleme pri drugem iskanju vogalov običajno povzročijo motnje pri zaznavanju stanja cevk.

Besides the inclination the center of the band is also estimated. Different positions of the band on the PASD determine four different angular shapes – rectangle, trapeze, trapezoid, etc. An example of the band situation on the PASD forming a trapeze shape is shown in Figure 33. The center of the band is estimated on the basis of the side with maximum length (between corners C1 and C4) and its left-hand (side between C1 and C2) and right-hand (side between C4 and C3) neighboring sides. The average value of the projections of the left-hand and right-hand neighboring sides to the line orthogonal on the side with the maximum length is calculated. The center of the band is determined as a point that is placed at a half of the average value of the projections of the left-hand and right-hand neighboring sides on the line that is perpendicular to the side with the maximum length and crosses the maximum length side at its middle.

If the number of corners found is larger than four the corner searching is activated again. If four corners are not determined in the second search then the procedure is stopped.

Problems with the corner determination in the second search are usually caused by disturbances in the state detection of the tubes.

1.2.2 Gibanje vzdolž dolžine traku s krmiljenjem usmeritve traku s povratno zvezo

Kompenzacija neželenih vrtenj traku med vzdolžnim gibanjem je izvedena v tako imenovani sklenjeni zanki meritev in delovanj.

Krmiljenje usmeritve traku s povratno zvezo smo izvedli na primeru gibanja vzdolž dolžine traku nazaj. Najdaljša stranica traku leži vzdolž osi x NPAP v začetni legi. V tem primeru lahko uporabimo vrtilno gibanje v levo in v desno s premikom nazaj za kompenzacijo neželenih vrtenj med vzdolžnim gibanjem. Tako je sklenjena zanka sestavljena iz določanja središča traku in njegovega nagiba. Če je nagib traku večji od 0,11 v rad, tedaj izvajamo rotacijsko gibanje desno. Če pa je nagib traku manjši od –0,11 v rad, tedaj izvajamo vrtilno gibanje levo. Po končnem zaporedju vrtilnega gibanja na levo in na desno se krmilna zanka ponovi s ponovnim določanjem središča traku in njegovega nagiba.

1.2.2 Translational Motion Along the Length of the Band with Closed-Loop Orientation Control

The compensation of undesired band rotations during band translational motion is achieved in a so-called closed loop of measurements and actions.

The closed-loop band-orientation control was implemented for the case of translational motion backward along the length of the band. The longest side of the band lies along the x-axis of the PASD in the initial situation. Rotational motion to the left and to the right with translational motion backward could be used for the compensation of undesired rotations during translational motion in this case. So, the closed loop consists of the detection of the center of the band and its inclination. If the inclination of the band is between the values -0.11 and 0.11 [rad] then translational motion to the left is activated. If the inclination of the band is higher than 0.11 [rad] then rotational motion to the right is activated. And if the inclination of the band is lower than –0.11 [rad] then rotational motion to the left is activated. After a finite sequence of rotational motion to the left and to the right the control loop repeats, beginning with the detection of the center of the band and its inclination.

1.2.3 Povzetek

Eksperimentalni rezultati so pokazali izboljšano obnašanje usmeritve pri krmiljenju traku s povratno zvezo med gibanjem vzdolž dolžine traku v primerjavi z gibanjem vzdolž dolžine traku brez krmiljenja usmeritve s povratno zvezo. Usmeritev traku med gibanjem nazaj ima približno vrednost,

1.2.3 Summary

Experimental results have shown improved band-orientation behavior during the translational motion along the length of the band with closed-loop orientation control in comparison to the orientation behavior during translational motion along the length of the band without orientation control. The angle of rotation of the band during določeno z območjem kota zasuka med -0,11 in 0,11 v rad. Vzdolžno gibanje traku nazaj se ne ustavi zaradi kompenzacije neželenih vrtenj, ker se med vrtenjem trak premika v isti smeri. Tako preklapljanje med vrtilnim gibanjem na levo in na desno z vzdolžnim gibanjem nazaj povzroča gibanje traku nazaj.

Žal se je med opisanim krmiljenjem usmeritve traku s povratno zvezo pojavilo neželeno premikanje traku v smeri y referenčnega koordinatnega sistema NPAP. Za kompenzacijo traku, ki drsi v smeri y NPAP, moramo vključiti v krmiljenje s povratno zvezo vzdolžno gibanje na temelju vrtenj, opisano v razdelku 1.1.3.

translational motion backwards is around the value determined with inclination values -0.11 and 0.11 (rad). The translational motion backwards of the band does not stop because of the band-rotation compensation since during the rotation the band moves in the same direction. So, only switching between rotational motion to the left and to the right with translational motion backwards produces translational motion backwards of the band.

Unfortunately, the sliding of the band in the y direction of PASD appeared during the described closed-loop control experiment. For the compensation of the band sliding in the y direction of the PASD the translational motion based on the rotations described in section 1.1.3 had to be incorporated into the closed-loop control algorithm.

2 SKLEP

V prispevku smo predstavili tri tehnike krmiljenja brez povratne zveze gibljivega predmeta (traku PVC) na ravni površini NPAP: gibanje vzdolž dolžine traku, gibanje vzdolž širine traku in vrtilno gibanje traku (okoli osi z). Med vrtenjem traku in premikanjem traku vzdolž širine traku se hkrati izvaja tudi premikanje vzdolž dolžine traku. Preobračanja traku na NPAP nismo obravnavali.

Preskusi s krmiljenjem gibanja traku brez povratne zveze so pokazali, da se pojavljajo med krmiljenjem brez povratne zveze mnoge motnje, ki povzročajo odstopanje od želenega gibanja. Na primer, med gibanjem vzdolž dolžine traku se občasno pojavi vrtenje traku. Zato smo v naslednjem koraku uporabili informacijo o gibanju traku za izvedbo tehnike krmiljenja s povratno zvezo.

Izvedli smo krmiljenje usmeritve traku s povratno zvezo med gibanjem vzdolž dolžine traku. Eksperimentalni rezultati so pokazali izboljšano obnašanje usmeritve med gibanjem vzdolž dolžine traku pri uporabi krmiljenja s povratno zvezo usmeritve traku v primerjavi z obnašanjem usmeritve traku pri gibanju vzdolž dolžine traku krmiljenja s povratno zvezo usmeritve traku. Natančnost krmiljenja usmeritve traku s povratno zvezo je odvisna od ločljivosti, s katero lahko določimo usmeritev naklon traku na NPAP.

Nekateri problemi so ostali nerešeni in jih bo v prihodnosti treba razrešiti, npr.: neželen premik traku v smeri osi y referenčnega koordinatnega sistema med krmiljenjem usmeritve traku s povratno zvezo. Nato je treba še preveriti gibanje traku na NPAP s površinami velikih izmer, velikim številom cevk in manjšim premerom cevk ter raziskati možnosti povečanja hitrosti gibanja. In nazadnje želimo celotnemu sistemu krmiljenja NPAP dodati še inteligentne tehnike krmiljenja, sledenje tirom, izogibanje oviram ipd.

2 CONCLUSIONS AND FUTURE RESEARCH

Three open-loop control techniques for the motion of a flexible object (PVC band) on the flat surface of PASD are presented in this paper: the translation along the length of the band, the translation along the width of the band and the rotation (around z-axis). Translation of the band along the length of the band takes place during rotation of the band and translation along the width of the band. Flipping of the band was not considered.

Experiments with open-loop control of band motion have shown that during the open-loop control several disturbances appear causing deviations from the desired motion. For instance, during translational motion the length of the band occasionally rotates. Therefore, in the next step feedback information about band orientation is used to implement closed-loop control.

Closed-loop control was applied to the orientation of the band during translational motion along the length of the band. Experimental results showed improved orientation behavior during translational motion along the length of the band with closed-loop band-orientation control in comparison to the translational motion without orientation control. The accuracy of the closed-loop orientation control of the band depends on the resolution with which the orientation and inclination of the band is determined.

Some problems were not solved and remain to be solved in the future, for instance: undesired band motion in the y direction of the reference coordinate system during closed-loop band-orientation control. Next, the motion of the band on the surface of the PASD with bigger x and y dimensions, a larger number of smaller tubes and an increase of the motion speed still has to be considered. And finally, intelligent control techniques, trajectory tracking, obstacle avoidance are desirable for the complete PASD system.

Zahvala

Projekt razvoja prototipne naprave NPAP je bil med drugim financiran tudi v okviru programa Fulbright-

Acknowledgment

The prototype PASD development project was funded by the Fulbright Scholar Program and ovih štipendij in je bil izveden v Laboratorijih Centra za tehniko avtomatizacije Središča za napredne tehnologije države New York na Politehničnem inštitutu v Rensselaer-u. Avtorji članka bi se radi posebej zahvalili vsemu osebju, ki je karkoli prispevalo k razvoju NPAP v Centru za tehniko avtomatizacije, posebej prof. Hary-ju Stephanou, Tobias-u Winther-ju in Ben-u Potsaid-u.

was carried out at the Laboratories of the Center for Automation Technologies, A New York State Center for Advanced Technology, Rensselaer Polytechnic Institute. The authors would like to thank to all the personnel involved at the Center for Automation Technologies, especially to Harry Stephanou, Tobias Winther and Ben Potsaid.

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Prejeto: Received: 3.4.2002

Sprejeto: Accepted: 20.9.2002