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Naprava in postopek za kalibriranje členkastih koordinatnih merilnih naprav

Apparatus and a Procedure to Calibrate Coordinate Measuring Arms

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Razvita je metoda za povečanje absolutne natančnosti prenosnih koordinatnih merilnih naprav z rotacijskimi osmi. Predlagana je povsem nova metoda, ki je zasnovana na kalibracijskih meritvah vzdolž ravne črte, nastavljive v različnih prostorskih smereh. V ta namen smo razvili novo zelo natančno kalibracijsko napravo, s katero je mogoče zbrati verodostojno število pozicijskih merilnih vrednosti, ki jih potrebujemo za izvedbo kalibriranja. Identifikacija parametrov je bila nato izvedena s kalibracijskim programskim paketom RoboCal. S tem prispevkom je pokazano, da s predlaganim postopkom kalibriranja in z uporabo nove zelo natančne kalibracijske priprave lahko izrazito izboljšamo natančnost pozicioniranja členkastih koordinatnih merilnih naprav. To je potrjeno tudi s preskusi.

(Ključne besede: naprave merilne koordinatne, naprave prenosne, kalibriranje, meritve ravnosti)

A technique for increasing the absolute accuracy of portable, coordinate measuring arms with exclusively rotational axes was developed. This new technique is based on calibration measurements along a straight line that is adjusted in various spatial directions. For this reason a special, new, high-precision calibration apparatus was developed to collect a representative quantity of accurate data needed for the successful calibration. Parameter identification was carried out using the RoboCal calibration software. The calibration procedure using the high-precision calibration apparatus can improve the pose accuracy of the coordinate measuring arm drastically. This was also confirmed by our experiments.

(Keywords: coordinate measuring devices, portable devices, calibrations, straightness measurements)

0 UVOD

Prenosne ročno gnane členkaste koordinatne merilne naprave (ČKMN - Coordinate Measuring Arm-CMA) z rotcijskimi osmi so se uspešno uveljavile v merilni tehniki, kjer potrebujemo tridimenzionalne rezultate meritev položaja [1]. Zaradi svoje kinematične strukture odprte verige členkastih mehanizmov ne dosegajo velike togosti in s tem velike absolutne natančnosti pozicioniranja, kakor je to običajno za kartezične koordinatne merilne naprave (KKMN - Coordinate Measuring Machine CMM). Vendar pa že sama struktura mehanizma, majhna teža, velika prilagodljivost, prenosljivost in dobra priročnost ČKMN omogočajo, da te naprave uporabimo na povsem novih področjih geometrijskega merjenja. Da bi s pridom izkoristili vse prednosti in pozitivne lastnosti teh naprav, obenem pa njihovo uporabo razširili tudi na področje, na katerem je potrebna večja absolutna natančnost merjenja, je treba absolutno natančnost pozicioniranja sedanjih naprav ČKMN izboljšati.

Najpomembnejša lastnost vsake merilne naprave je njena zmožnost natančnega pozicioniranja. Za naprave z rotacijskimi osmi pomeni ponovljivost poze

0 INTRODUCTION

Portable, manually driven, coordinate measuring arms (CMAs) with exclusively rotational axes have been successfully introduced into many measuring applications where three-dimensional geometrical data are required [1]. This is true that an open kinematic chain with more axes cannot ensure such high rigidity and accuracy of the mechanical structure as in common Cartesian coordinate measuring machines (CMMs); however, structural compactness, low weight, good flexibility, portability and good dexterity allow CMAs to be applied to completely new areas. To take advantage of these positive characteristics and to expand their use to measuring applications where higher measuring accuracy is demanded, the absolute accuracy of the positioning has to be increased.

To obtain an insight into the characteristics of devices, particularly devices with rotational axes, the most important feature is pose repeat-

(PP glede na standard ISO 9283; poza - skupni izraz za pozicijo in orientacijo) glavni natančnostni podatek. Ta vrednost pove, kakšna je zmožnost naprave pri ponavljajočem se prihajanju v isto pozo v nespremenjenih razmerah premikanja in okolice. Preskusi, izvedeni na prototipu merilne naprave ČKMN , kažejo, da je z uporabo posebnih materialov in z ustrezno konstrukcijsko rešitvijo mogoče doseči razmeroma dobro ponovljivost tudi pri napravah z odprto kinematično verigo [2]. Meritve natančnostnih lastnosti različnih ČKMN potrjujejo domnevo o prevladujočem vplivu sistematičnih pogreškov. Tako pomeni ponovljivost tisto mejno vrednost, ko začnejo prevladovati naključni pogreški, če so okoliščine nespremenjene. S tem določajo meritve ponovljivosti mejo izboljšanja absolutne natančnosti poze (AP glede na standard ISO 9283), ki jo lahko dosežemo s postopki kalibracije in kompenzacije sistematičnih deležev pogreškov.

Absolutna natančnost pozicioniranja ČKMN je odvisna predvsem od natančnosti izdelave in od verodostojnosti modela, ki je uporabljen za preračun dejanske poze. Za zagotovitev kakovosti izdelave in za natančno identifikacijo parametrov modela ČKMN, so potrebne natančne meritve in napredne metode modelno zasnovane identifikacije parametrov [3]. Ti postopki in metode so zajeti v tehniki, ki jo imenujemo kalibriranje mehanizmov in jo poznamo s področja robotike kot robotsko kalibriranje [4].

V robotiki se je mnogo avtorjev ukvarjalo s postopki kalibracije in kompenzacije ([5] do [7]). Rezultati preskusov v robotiki na mehanskih strukturah z rotacijskimi osmi kažejo, da ti postopki omogočajo izboljšavo absolutne natančnosti mehanizma blizu meje ponovljivosti. S praktičnega vidika pomeni postopek kritično točko pri zmožnosti merilne naprave, ki jo uporabljamo za kalibriranje. Ta mora zbrati potrebne podatke poz v določenem prostoru v ustreznem nivoju natančnosti. Kalibracijski programski paket je razvit tako, da lahko sodeluje s poljubno kalibracijsko merilno napravo. Ker ustrezne naprave za kalibriranje členkastih koordinatnih merilnih naprav ni, smo se odločili, da zanje razvijemo novo zelo natančno kalibracijsko pripravo in oblikujemo ustrezen postopek modelno zasnovane identifikacije parametrov in s tem vplivamo na občutno povečanje natančnostnih lastnosti ročnih večstopenjskih členkastih merilnih naprav, ki so mehansko podobne členkastim robotom.

1 NOVA ZELO NATANČNA KALIBRACIJSKA NAPRAVA

Sedanje ČKMN kalibriramo in testiramo zelo različno. Za kalibriranje in testiranje ČKMN glede natančnostnih lastnosti v prostoru lahko uporabimo metodo s posebeno kalibracijsko oziroma testno šablono ali pa metodo s kroglami na palici ([8] in [9]). Nadalje lahko uporabimo metodo kalibriranja z uporabo artefaktov [10]. Preučevali in testirali smo

ability (RP according to ISO 9283). This value characterises the device’s capability to attain the same pose n-times under the same conditions. Experiments on CMAs show that the use of special materials and the choice of convenient construction solutions offer the possibility of achieving a relatively good repeatability performance, even for devices with an open kinematic chain structure [2]. Accuracy measurements carried out on different CMAs confirmed the mostly systematic character of the remaining sources of error. In this context, repeatability represents a limitation, where stochastic deviations under constant environmental conditions become dominant. Therefore, the repeatability measurement determines the limitation of pose-accuracy (AP according to ISO 9283) improvement by means of the compensation of systematic error parameters, i.e. calibration.

Absolute positioning accuracy depends mostly on the quality of the manufactured CMAs and how well the model used for the pose calculation matches with reality. To ensure quality of manufacturing and to accurately identify CMA model parameters, advanced measuring procedures and model-based parameter-identification methods are required [3]. These procedures and methods are summarised in the techniques called device calibration, known in robotics as robot calibration [4].

Many authors have studied calibration and compensation procedures in robotics ([5] to [7]). The results of experiments on robot mechanism structures with rotational axes show that this provides us with the possibility to improve absolute accuracy performance nearly up to the repeatability limit. From the practical point of view, the critical point of this procedure is the capability of the measuring device used for the calibration to collect all the needed positional data in space with the demanded accuracy level, whereas the calibration software can cooperate with any measuring device. Therefore, we decided to design and develop a new high-precision calibration apparatus, and formulate an appropriate advanced model-based parameter-identification procedure for the calibration of CMAs in order to lead to significant improvements in the accuracy characteristics of such manually driven multi-axis measuring devices which have many similarities to robots.

1 NEW HIGH-PRECISION CALIBRATION APPARATUS

Existing CMAs are calibrated and tested very differently. A special calibration and testing jig or an adapted ball-bar approach for establishing the degree of volumetric accuracy may be used ([8] and [9]). Another calibration method involves a procedure using different artefacts [10]. Calibration with a Cartesian CMM was also studied; however, the tudi možnost kalibriranja z uporabo KKMN. Vendar zaradi velikega raztrosa merilnih rezultatov, katerih vzrok je elastičnost sistema KKMN kot posledica reakcijskih sil, ki se pojavijo ob premikanju merilne naprave ČKMN, merilni rezultati niso uporabni [11].

Na podlagi raziskav na tem področju smo ugotovili, da ustrezno rešitev ponuja samo robustna mehanska oprema za merjenje in vodenje vrha ČKMN vzdolž referenčne črte, ki jo je mogoče v prostoru poljubno usmerjati. Za potrditev te domneve smo izvedli preskus na sedanjem dolžinskem primerjalniku [12]. Z uporabo primerjalnika, ki je fiksno nameščen v klimatizirani kabini, smo uspešno izvedli meritve ponovljivosti in natančnosti prototipa ČKMN vzdolž ravne črte v treh različnih vodoravnih legah [13]. Ker omejeno število vodoravnih črt ne da verodostojnih rezultatov, potrebnih za oceno natančnosti naprave v celotnem področju gibanja, smo se odločili za razvoj nove zelo natančne kalibracijske priprave za testiranje in kalibriranje členkastih merilnih naprav z rotacijskimi osmi, ki jo je mogoče nagibati pod različnimi koti v prostoru.

Podatek, ta je ključen pri razvoju nove kalibracijske priprave, je podan z mejo pozicijske natančnosti, ki jo mora kalibracijska priprava doseči. Ta meja je bila definirana na temelju meritev ponovljivosti na sedanjem prototipu ČKMN. Preskus, ki je bil izveden na sedanjem dolžinskem primerjalniku v klimatiziranem prostoru v nespremenjenih razmerah, je pokazal, da znaša ponovljivost v najbolj ugodnem delu delovnega prostora r = 2,5 μm za statistično verjetnost ±2σ glede na standard ISO 9283 [13]. Nadalje smo raziskali vse možne vzroke, ki lahko povzročajo odstopanja pri samih kalibracijskih meritvah. V ta namen smo izvedli veliko število različnih poskusov in simuliranj. Ugotovili smo, da so celotna odstopanja sistema najbolj povezana s spremembami v okolici, z učinkovanjem vplivov notranjih in zunanjih sil in momentov ter z odstopki geometrijske nenatančnosti posameznih elementov [14].

Celoten sistem je sestavljen iz premega nosilca s podporno konstrukcijo, sistema vležajenih sani, pogonskega sistema in merilnega sistema, ki je nameščen ločeno glede na premi nosilec. Glavna naloga sistema premega nosilca je natančno vodenje sani glede na zahteve orientacijskega odstopanja vzdolž ravne črte v prostoru. V ta namen je izbran votel keramični nosilec dolžine L=2000 mm s površinami, obdelanimi v tolerančnem območju premosti manjše od 1 μm/m. Računska simuliranja, ki so bila izvedena na izbranem nosilcu, so pokazala, da odstopanja od premosti zaradi vpliva lastne teže nosilca in zaradi vpliva zunanjih sil ne presegajo vrednosti 1 μm oziroma kota 0,5 kotnih sekund [15].

Ker pa konstrukcijska rešitev upošteva tudi merjenja v navpični smeri, je pogonskemu sistemu sani dodana tudi protiutež. Nameščena in vodena je na posebnih vodilih znotraj keramičnega nosilca in

measuring results did not prove to be useful since considerable variation in the results appeared, this was caused by the deflection of the CMM system as a consequence of reaction forces caused when moving the CMA [11].

From the above investigations in this area it was clear that only robust mechanical equipment for measuring and guiding of CMAs along any reference line adjustable in various spatial directions can offer a promising high-precision solution. To confirm this supposition, an existing high-precision length comparator was used [12]. Using this fixed high-precision length comparator in a climatic chamber, repeatability and accuracy measurements of the CMA were successfully carried out along some horizontal straight lines [13]. While a limited number of horizontal lines cannot give representative results for an assessment of a complete device, we decided to design and develop a new high-precision calibration apparatus for testing and calibrating CMAs, which can be adjusted in various spatial directions.

When starting to design the new calibration apparatus we set the limits of positional accuracy that the calibration apparatus should achieve. This limit was based on repeatability measurements made on an existing CMA. The experiment, which was made on a high-precision length comparator in the stable environment of a climatic chamber, showed that the repeatability in the most advantageous workspace amounts to r = 2.5 μm for a statistical probability of ±2σ according to ISO 9283 [13]. Another important point was to establish all the possible sources of deviation. Consequently, many experiments and simulations were made to determine the deviations which are mainly associated with changes in the environmental conditions, with internal and external sources of forces and moments, and with geometrical deviations of individual elements [14].

The whole system consists of a line gauge beam with a support arrangement, a sled-bearing system, a drive system and a measuring system located separately from the line gauge beam. The main task of the line-gauge-beam system is to guide the sled exactly within the demanded limits with respect to deviations in orientation along a straight line. A hollow ceramic beam length of L = 2000 mm with surfaces manufactured to a tolerance of 1 μm/m was chosen. Simulations showed that the straightness deviation under its own weight and under external forces did not exceed a value of 1 μm or an angle of 0.5 arc seconds [15].

Since it should also be possible to measure in the vertical direction, a counterweight was added to the sled-bearing drive system. It was located and guided on separate shafts inside the ceramic beam and preko pogonskega sistema povezana s sanmi. Vodila protiuteži so nameščena povsem neodvisno od keramičnega nosilca in tako ne vplivajo na deformacijo keramičnega nosilca.

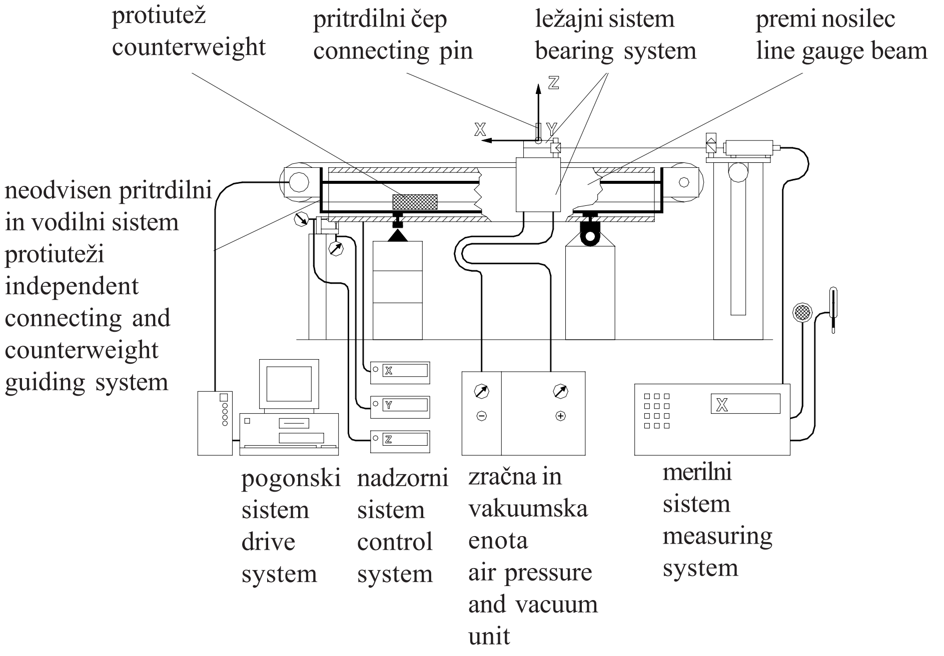
Vležajenje sani je izvedeno z zračnim ležajem tipa L z dodatnim vakuumskim delom, ki poveča togost ležaja, zaradi majhne in priročne konstrukcije je taka rešitev tudi primerna za povezavo s ČKMN. Izvedba konstrukcije tipa L omogoča pritrditev podpor nosilca v Bessel-ovih točkah in s tem možnost premikanja sani vzdolž celotne dolžine nosilca. Pri ČKMN s petimi osmi je za prosto premikanje vzdolž ravne črte v prostoru potrebnih šest prostostnih stopenj. Problem ene manjkajoče rotacije smo rešili z dodatnim rotacijskim vakuumsko prednapetim zračnim ležajem, na katerega je nameščen priključni čep za pritrditev ČKMN.

Merilni del sistema v grobem sestavljata laserski interferometer, ki je namenjen za merjenje položaja v smeri X in nadzorni sistem, ki ga sestavljajo merilniki pomikov premega nosilca v smereh Y in Z. Edina naloga tega sistema je zaznati premike, če se pojavijo, ki jih povzroča obremenjevanje kalibracijske priprave med samim merjenjem s strani ČKMN. Da se tem vplivom kar najbolje izognemo, smo pozicijski merilni sistem postavili na samostojen in neodvisen podstavek. Ker objekt, ki ga merimo, povzroča sile, te lahko deformirajo celoten nosilec in podporno konstrukcijo, je glavna prednost neodvisno postavljenega pozicijskega merilnega sistema, da deformacije ne vplivajo na rezultat pozicijske meritve. Celotna naprava je prikazana na sliki 1.

connected through a drive system with the sled. These separate shafts allow for the complete separation of the counterweight guide from the ceramic beam and thus avoid any deflection of the ceramic beam.

For the sled-bearing system we decided to use an L-type sled with a preloaded vacuum-air bearing, which is very rigid, small, light and convenient for connecting to CMAs. Due to its L-type construction it was possible to support the line gauge beam in the Bessel-points and in spite of the supports allow the sled-bearing system to make free movement along the whole beam length. For CMAs with five axes for free movement along any straight line in space with constant orientation, one degree of freedom is missing. To solve this problem we added an additional high-precision rotational preloaded vacuum-air bearing equipped with a connecting pin for connection with a CMA.

The measuring part of the system consists of a laser interferometer to measure longitudinal distance in the X direction and a control system, which contacts the line-gauge-beam surfaces in the Y and Z directions. The only task of this system is to measure displacements, if any occur, resulting from the loading of the high-precision calibration apparatus by the CMA. To achieve the best performance of the whole high-precision calibration apparatus we decided to locate the position measuring system separately from, and independently of, the line-gauge-beam system. Since the object to be measured causes forces which deflect the whole beam and the support-construction, the main advantage of a separately located position-measuring system is that deflections have no influence on the position-measuring results. The whole arrangement is presented in Fig. 1.



Sl. 1. *Celotna postavitev nove kalibracijske naprave, nastavljive v različnih prostorskih smereh*
Fig. 1. *Complete arrangement of the new calibration apparatus, oriented in various spatial directions*

Za določitev razširjene negotovosti meritve smo razvili poenostavljen vendar verodostojen teoretični model kalibracijske priprave za primer nadzorovanih pogojev okoliščin. V izračunih so negotovosti meritev razporejene v pozicijske in orientacijske. Najbolj neugodne rezultate preračuna smo dobili pri pozicijskem odstopanju v smeri *Y*. Kadar je merilni sistem nagnjen za okoli 50 stopinj, je podpora 2 zelo visoka. Teoretični odstopek v smeri *Y* lahko v ekstremnem primeru znaša na vrhu merilnega področja tudi Sb_{yex}= 0,024 mm. V takem primeru je neizogiben poseben dodaten merilni sistem, ki meri odstopanja v smereh *Y* in *Z*. V bolj ugodnih primerih pa teoretičen preračun na poenostavljenem vendar verodostojnem modelu da boljše rezultate razširjene negotovosti meritve. V smeri *X* znaša U_x = 0,00218 mm, v smeri *Y* U_y = 0,00271 mm in v smeri *Z* U_z = 0,00336 mm. Vrednosti pri orientacijskem delu pa so: U_{Rx} = 7,1 kotne sekunde za rotacijo okoli osi *X*, U_{Ry} = 1,2 kotne sekunde okoli osi *Y* in U_{Rz} = 0,9 kotne sekunde za rotacijo okoli osi *Z* [20].

Za potrditev teoretičnih postavk in preračunov modela in za določitev eksperimentalne negotovosti meritve zelo natančne kalibracijske naprave, so potrebne različne meritve [16]. Najboljšo oceno glede negotovosti lahko naredimo na podlagi meritev premosti vodenja sani kalibracijske naprave, obremenjene s ČKMN. Za merjenje premosti smo uporabili avtokolimator in elektronske libele. Dodatno smo z merilniki pomikov v nekaterih značilnih točkah nosilca merili tudi pozicijaska odstopanja v smereh *Y* in *Z*.

Meritve so bile izvedene v laboratorju v nadzorovanih razmerah. Pri tem sta bili kalibracijska priprava in ČKMN postavljeni na skupno granitno mizo. Tako so bile izpolnjene vse zahteve glede nespremenjene medsebojne lege in stabilnosti obeh sklopov naprav. Pri meritvi je bila ČKMN v smeri *X* postavljena na sredino glede na kalibracijsko napravo in 622 mm oddaljena v smeri *Y*. Med samo meritvijo sta bili obe napravi medsebojno povezani. S tem je bila zelo natančna kalibracijska naprava tudi dejansko obremenjena. Prva merilna lega je bila izbrana v sredini nosilca. Sani smo nato pomaknili vzdolž nosilca in izvedli meritev na vsakih 100 mm. Pomiki so bili narejeni najprej v negativno smer *X* in nato v pozitivno smer *X* od enega konca nosilca do drugega, meritev pa končali v prvotni začetni točki. Po več ko petih ponovitvah meritve vzdolž celotne dolžine nosilca, so bile kotne vrednosti merjene z avtokolimatorjem in z elektronskimi libelami v diferencialnem vklopu statistično obdelane in na sliki predstavljene kot odstopanja srednje vrednosti premosti. Merilni sestav za merjenje premosti in kotnih odstopanj, obremenjen s ČKMN, je prikazan na sliki 2.

We developed a theoretical model to determine the expanded uncertainty of the measurement for a simplified but corresponding model of the high-precision calibration apparatus under controlled environmental conditions. In the calculation the uncertainties of the measurement were divided into positional and orientational parts. The most unfavourable results of the calculation of the positional part were obtained in the *Y* direction. When the measuring equipment is extremely inclined and support number 2 must be very high, the calculated deviation in the *Y* direction can be about Sb_{yex} = 0.024 mm in the extreme case at the top of the measuring area. In such a case a separate measuring system to measure this deviation would be indispensable. However, in less unfavourable cases the theoretical calculations performed on the simplified but corresponding model gave results for the expanded uncertainty of measurement in the *X* direction U_x = 0.00218 mm, in the *Y* direction U_y = 0.00271 mm, in the *Z* direction U_z = 0.00336 mm; and for the orientational part U_{Rx} = 7.1 arc seconds around the *X* axis, U_{Ry} = 1.2 arc seconds around the *Y* axis, and U_{Rz} = 0.9 arc seconds around the *Z* axis [20].

To confirm these theoretical suppositions and calculations and to verify the actual uncertainty of the measurement of the high-precision calibration apparatus, we carried out various measurements [16]. The best survey of uncertainty characteristics can be made by straightness measurements of the preloaded vacuum-air-bearing system loaded with a CMA. The straightness was measured with an autocollimator and with electronic inclinometers. In some characteristic positions the displacements were measured with length indicators, which contact the line-gauge-beam surfaces in the *Y* and *Z* directions.

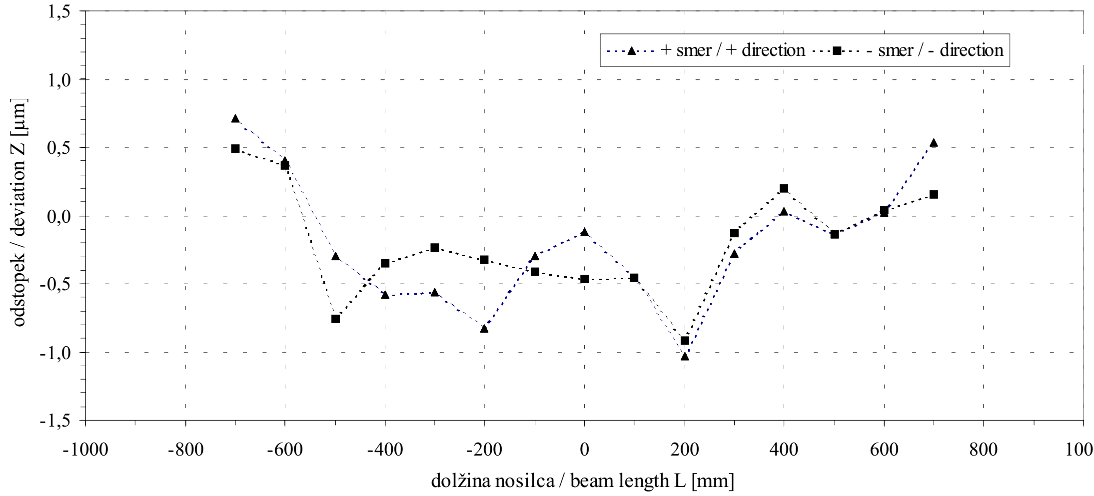
The measurements were carried out in a laboratory under constant environmental conditions where the high-precision calibration apparatus and the CMA were placed on the same granite table. In this way all the requirements for a constant and stable relationship between the two base coordinate systems were fulfilled. The CMA was put in the central area of the length measurement direction and 622 mm away from the beam centre line. During the measurement both devices were coupled together. In this case the CMA represented a load on the high-precision calibration apparatus. The first measuring position was chosen to be in the middle of the beam. The sled-bearing system loaded with the CMA moved along the beam and stopped every 100 mm. Movements occurred first in the negative *X* direction to one side of the beam then in the positive *X* direction on the other side and finally back to the previous initial position. After more than five repetitions of the same measuring procedure along the whole beam length, the angular changes measured with an autocollimator and with electronic inclinometers using differential switching were statistically processed and presented as mean values of the straightness deviations. The measuring set-up for straightness and angle deviation measurements when loaded with the CMA is presented in Fig. 2.

Sl. 2. *Ureditev merilnega mesta za merjenje odstopkov premosti in kotnih odstopanj, pri čemer so sani obremenjene s ČKMN*

Fig. 2. *Layout of the measuring set-up for straightness and angle deviation measurements when loaded with the CMA*

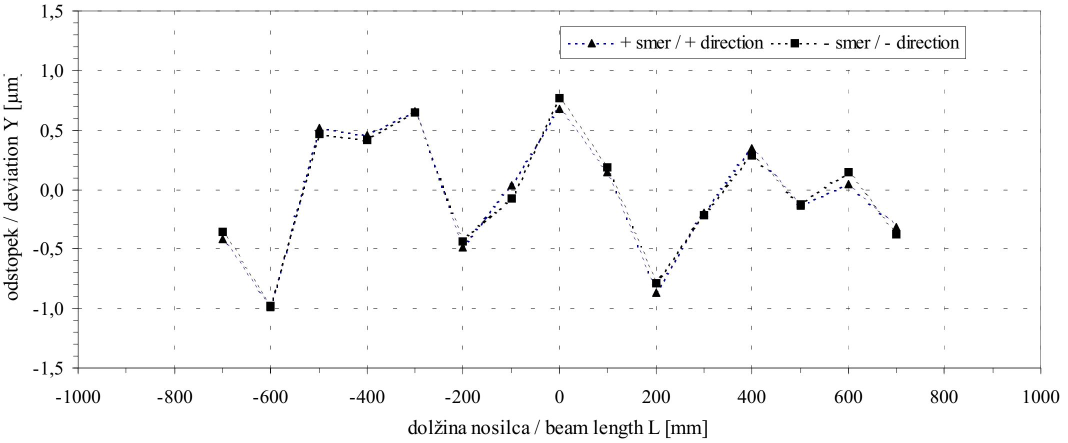
Rezultati odstopanj premosti kalibracijske naprave v smeri *Z*, ko je leta obremenjena s ČKMN, so prikazani na sliki 3. Standardni odklon rezultatov meritev z avtokolimatorjm v smeri Z v vseh pozicijah ne presega vrednosti za $2\sigma = 0,7$ µm. Rezultati meritev v smeri *Y*, ki so prikazani na sliki 4, so zelo podobni. Standardni odklon 2σ za meritve v smeri *Y* ne presega vrednosti 0,6 µm. Rezultati srednjih vrednosti meritev kotnih odstopkov β vzdolž osi *X*, ki so bili merjeni z elektronskimi libelami v diferencalnem vklopu, so prikazani na sliki 5. Med meritvami smo preverjali tudi pomike nosilca na več ključnih mestih. Opazne so bile samo zelo majhne (v našem primeru zanemarljive) spremembe pozicije zaradi upogibanja nosilca pod bremenom sani. Drugih omembe vrednih pomikov v drugih smereh nismo zaznali.

The results for the straightness deviation of the high-precision calibration apparatus in the *Z* direction when connected to the CMA as an external load are presented in Fig. 3. The standard deviation of the results obtained by the autocollimator in the *Z* direction in all positions was not larger than $2\sigma = 0.7$ µm. The situation for the results in the *Y* direction, presented in Fig. 4, was very similar. For the *Y* direction the standard deviation 2σ was not larger than 0.6 µm. The results for mean values of the angular deviations β, measured along the *X* axes with electronic inclinometers using differential switching, are presented in Fig. 5. During the measurement we checked the displacements of the beam gauge at several key locations. Only bending changes at the expected level (in our case negligible) were noted, and no large displacements in the other directions were observed.

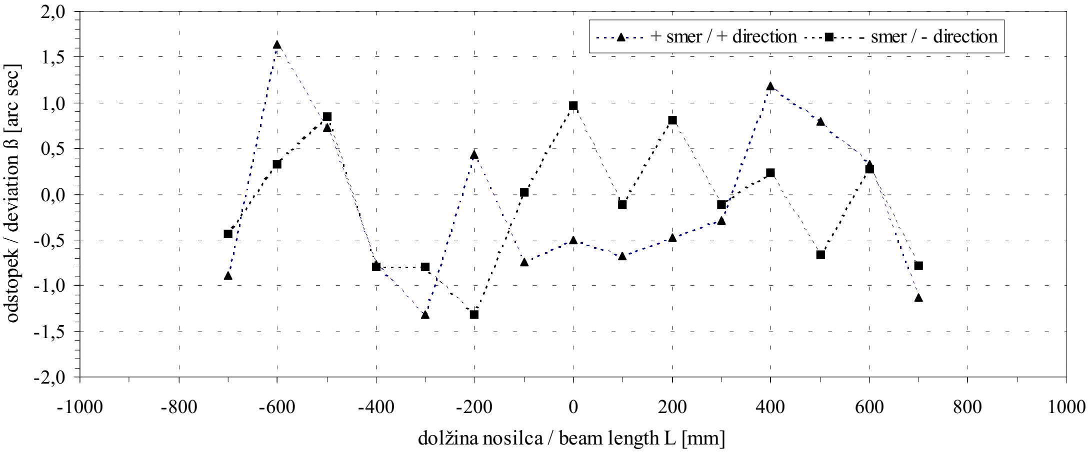


Sl. 3. *Rezultati meritev premosti v smeri Z*

Fig. 3. *Results of straightness measurements in the Z direction*



Sl. 4. *Rezultati meritev premosti v smeri Y*
Fig. 4. *Results of straightness measurements in the Y direction*



Sl. 5. *Rezultati meritev kotnih odstopanj okoli osi X*
Fig. 5. *Results of angular deviation measurements about the X axis*

Za konec smo celotno zelo natančno kalibracijsko napravo postavili na podpore in nagnili keramični nosilec za kot $\alpha = 50^{\circ}$. Ker smo v tej legi pričakovali opazne elastične deformacije zaradi obremenjevanja z zunanjimi silami in momenti naprave, ki jo merimo, smo pri preskusu posebno poudarili meritvi pomikov v smereh *Y* in *Z*. Preskus je pokazal, da čvrsta pritrditev podpor na betonsko podlago in toga pritrditev zamenljivih delov podpor sestavljajo razmeroma stabilno strukturo, tako da vrednosti pomikov nikjer ne presežejo meje 2 µm z upoštevanjem navedenih pogojev obremenjevanja.

Rezultati meritev zelo natančne kalibracijske naprave so pokazali, da so teoretični izračuni in pričakovanja pravilna in resnična. Tako lahko novo natančno kalibracijsko napravo predlagamo kot primeren referenčni merilni sistem za kalibracijska merjenja naprav s členkasto kinematično strukturo, kakor so na primer merilni roboti ali preostale ročne členkaste merilne naprave.

Finally, we put the whole high-precision calibration apparatus on supports and in a position inclined by $\alpha = 50$ degrees. Since, here, significant elastic deformations through changeable loading from the device to be measured can appear, we measured displacements caused through loading with the CMA, particularly in the *Y* and *Z* directions. Because of the solid fixing of the supports to the concrete base and the rigid connection of the exchangeable support parts, we were successful in keeping these values under the 2 µm level for the stated loading conditions.

The experiments on the real high-precision calibration apparatus showed that the theoretical expectations were successfully achieved. Thus the new high-precision calibration apparatus can be taken as an appropriate reference measuring system for calibration measurements of devices with unconventional kinematic structures, such as measuring robots, or in particular, manually driven CMAs.

2 KALIBRACIJSKE MERITVE

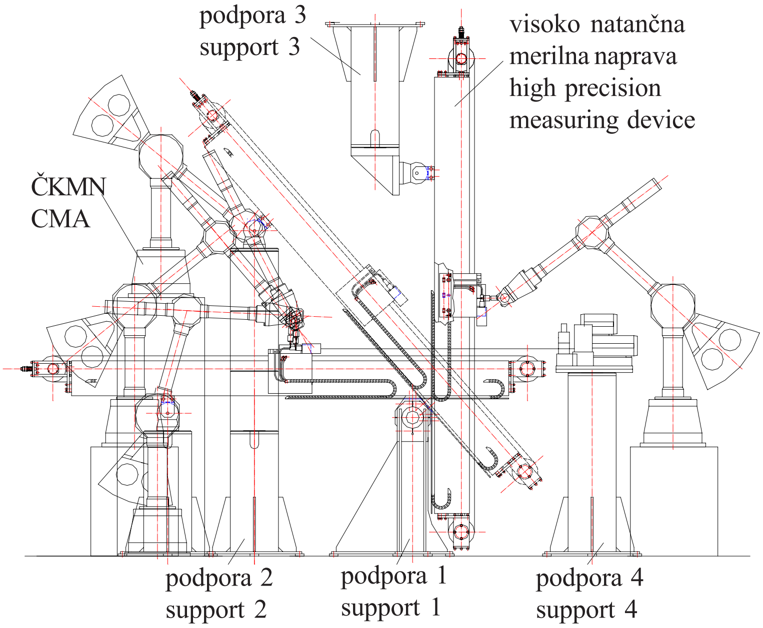
Za uspešno in kakovostno izvedbo kalibriranja z razvito kalibracijsko napravo in predlaganim postopkom potrebujemo določeno število kalibracijskih meritev. Te meritve naj bodo izvedene v več različnih pozah in izbrane tako, da merilna naprava CMA zavzame vedno različno konfiguracijo mehanizma. Med premikanjem v naslednjo pozo je priporočljivo, da se vrtijo vse osi členkov.

Pri kalibracijskih meritvah smo zelo natančno kalibracijsko napravo prek opisanih podpor pritrdili na betonsko podlago. ČKMN smo postavili na isto podlago in jo priključili prek priključnega čepa na kalibracijsko pripravo. Višino smo spreminjali tako, da smo ČKMN postavili neposredno na betonsko podlago ali pa jo položili na podstavek. Iz praktičnega gledišča jo je bolj primerno postaviti v različne lege ob kalibracijski pripravi, kakor pa nasprotno. Koordinate *X* in *Y* in vrtenje okoli osi *Z* tako preprosto spreminjamo s premikanjem oziroma vrtenjem baznega koordinatnega sistema ČKMN (s podstavkom ali brez njega) na betonski podlagi. Konstrukcija kalibracijske priprave omogoča le vrtenje nosilca okoli osi *Y* in s tem možnost nastavljanja kota nagiba. Določen nagib dosežemo tako, da na prvi podpori zasučemo os in s tem nagnemo celotni nosilec. Z vstavitvijo dodatnih zamenljivih delov na drugem podstavku pritrdimo nosilec v nasprotni podporni točki. V ekstremnem primeru je kalibracijska priprava postavljena tudi navpično (sl. 6).

2 CALIBRATION MEASUREMENT

For a successful and quality calibration with the proposed apparatus and procedure, a certain number of calibration measurements are needed. These measurements should be performed in many different poses and be chosen so that the CMA always takes a different mechanical configuration. During the movement to another measuring pose it is recommended that all joints rotate.

To take into account all the above demands, the high-precision calibration apparatus with robust supports was placed and fixed to a concrete base. The CMA was positioned on the same base and connected through a connecting pin to the high-precision calibration apparatus. The CMA was placed directly on the base or lifted to a support. From a practical point of view it is more convenient to place the CMA at different locations around the high-precision calibration apparatus than to make it possible for this robust measuring device to be adapted for any possible measuring arrangement. Therefore the *X* and *Y* coordinates and the rotation about the *Z* axes can be easily changed through the movement and rotation of the CMA base coordinate system with (or without) its support on the concrete base. On the other hand, the construction of the high-precision calibration apparatus allows adjustments of the measuring and guiding beam system in various spatial directions. A desired inclination can be reached by turning the whole line-gauge-beam system about the horizontal axes of the first support and by insertion of additional exchangeable support parts into the second support. In an extreme case the high-precision calibration apparatus can also be placed in the vertical position (Fig. 6).



Sl. 6. *Zelo natančna kalibracijska naprava in ČKMN v različnih konfiguracijah in različnih legah za opravljanje kalibracijskih meritev v različnih položajih*

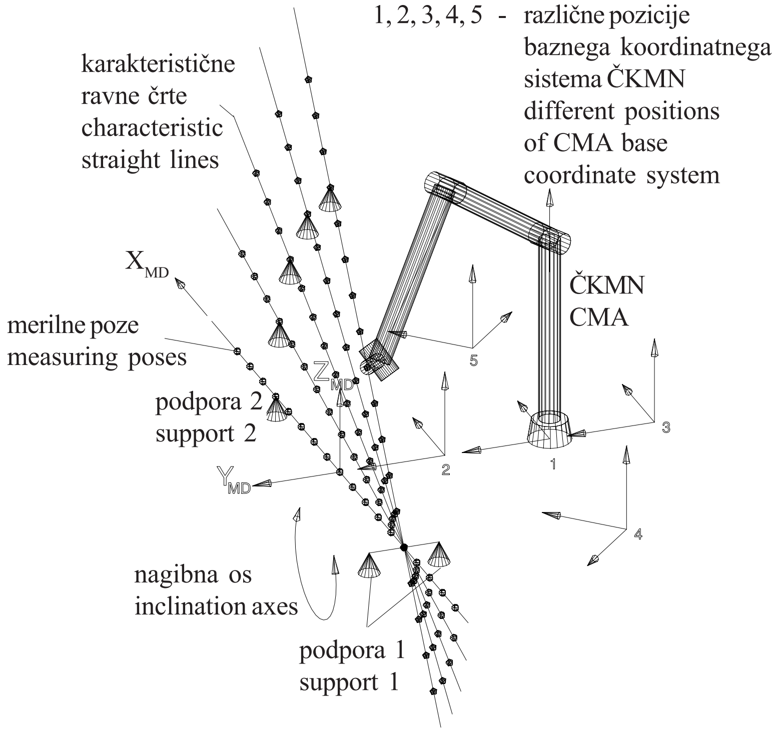
Fig. 6. *High-precision calibration apparatus and a CMA in different configurations and locations to carry out calibration measurements in different positions*

V primeru meritev v različnih vodoravnih legah, lahko višino ČKMN spreminjamo z vstavitvijo zamenljivih delov podstavka. V našem primeru smo jo postavili na granitno mizo ob kalibracijski napravi. Pomikanje ČKMN v naslednjo lego na granitni mizi in sprememba nagiba nosilca sta izvedeni ročno. Tako smo upoštevali razmerje med še razumno ceno in togostjo naprave.

Potek kalibracijskih meritev je prikazan na sliki 7. Pri tem smo izvajali meritve vzdolž različno nagnjenih ravnih črt, nastavljenih na kalibracijski napravi, spreminjali pa smo tudi lego in kot ČKMN glede na kalibracijsko napravo (sl. 7). Glede na opisan postopek smo zbirali podatke meritev razdalj, dobljenih z uporabo laserskega interferometra vzdolž nosilca v smeri *X* pri predpostavki, da se med meritvijo orientacija nosilca ne spreminja. Obenem smo zbirali tudi kotne vrednosti posameznih členkov ČKMN. Z namenom, da nadziramo morebitna odstopanja pravokotno na keramični nosilec v smereh *Y* in *Z*, smo pozicijska odstopanja merili z merilniki pomikov, ki so bili nameščeni na neodvisna stojala.

If measurements at different horizontal positions are needed the CMA support can be varied through exchangeable support parts or in our experimental case by placing the CMA on a stable granite table. Movement of the CMA to another location and readjustment of the inclination in our case was made manually, while a reasonable relationship between system robustness and the cost of the device was taken into account.

For the calibration measurements some characteristic straight lines that were adjusted in various spatial directions by different CMA base coordinate positions and rotations were chosen (Fig. 7). From these calibration measurements, laser interferometer distances along the line gauge beam at constant orientation carried out on the high-precision calibration apparatus and encoder angle values measured by the CMA were collected. In order to observe possible deviations orthogonal to the line gauge beam in the *Y* and *Z* directions, the displacement of the line gauge beam was measured with length indicators placed on separate stands.



Sl. 7. *Nekaj značilnih ravnih črt, nastavljenih v različnih prostorskih smereh pri različnih legah in usmeritvah ČKMN, ki jih uporabljamo pri kalibracijskih meritvah*

Fig. 7. *Some characteristic straight lines adjusted in various spatial directions by different CMA base coordinate positions and rotations used for calibration measurement*

3 RAZPOZNAVANJE PARAMETROV

Razpoznavanje parametrov je bilo izvedeno z uporabo kalibracijskega programa RoboCal, ki je bil razvit na Fraunhoferjevem inštitutu za proizvodne sisteme in konstrukcijsko tehnologijo (IPK) [17]. Ta

3 PARAMETER IDENTIFICATION

Parameter identification was carried out using the RoboCal calibration software that was developed by the Fraunhofer Institute Production Systems and Design Technology (IPK) [17]. This softprogramski paket omogoča razpoznavanje parametrov, ki pripadajo naslednjim podmodelom mehanizma: kinematični model, model pogona in model elastičnih deformacij [18]. Model pogona je sestavljen iz pogona posameznih členkov. RoboCal omogoča modeliranje sklenjenih kinematičnih verig znotraj posameznega pogona (ročični in drsni mehanizmi, paralelogrami), medtem ko je s programom mogoče modelirati celovite mehanske strukture z razklenjeno kinematično verigo, s pričetkom na podlagi in koncem na prirobnici (zaporedni mehanizem). Če to primerjavo razvijemo za naš primer, opazimo, da kalibracijska priprava in ČKMN v bistvu ustvarjata zaprto kinematično verigo (vzporedni mehanizem). Potemtakem ni mogoče izvesti razpoznave modela elastičnih deformacij, ker si preračun bremena zaradi obremenitve posameznih členkov zamišlja, da imamo opravka s prostim koncem kinematične verige.

3.1 Modeliranje

Preostala podmodela ČKMN sta kinematični model in model pogona. Kinematični model je popoln in primerljiv s kinematičnim modelom členkastega robota. Zatorej bomo oznako “zaporedno zapestje” uporabili za opis zadnjih dveh osi ČKMN in rotacijskega zračnega ležaja kalibracijske priprave. Oznaka “tarča” opisuje lokacijo, kamor je pritrjeno odbojno zrcalo laserskega interferometra. Model pogona opisuje razmerje med vrednostmi merilnega sistema v členku in relativnim kotom med posameznimi deli enega segmenta glede na drugega. Odnos je zapisan s stalnim prestavnim razmerjem, dodana pa je Fourierjeva aproksimacija, ki ponazarja morebitno odstopanje prestavnega razmerja. Zaradi zgornjih razlogov (preračun bremena si zamišlja prosti konec kinematične verige), se zračnost v zgibih ne razpozna. Izbira poz, v katerih naj bo opravljena meritev, prav tako pripada postopku modeliranja. Izbira vzorca poz predpisuje neko odvisnost, ki na ta način lahko pokrije podobno odvisnost zaradi parametra modela. Ta odvečnost povzroči defekt modelnega Jacobiana. Elementi te matrike so izpeljani iz položajev tarče glede na parametre modela. Najbolj primerno je, da odvečnost zaznamo in ji sledimo z uporabo razstavitve modelnega Jacobiana po singularnih vrednostih.

3.2 Funkcijska vrednost

V vsaki merjeni pozi *i* beremo vrednosti *h* iz merilnih sistemov posameznih členkov ČKMN in vrednosti iz meritve z laserskim interferometrom. S kalibracijo razpoznamo parametre modela *p*, ki minimizirajo vsoto vseh razdalj (Euklidove norme), ki jih dobimo kot razliko med položaji tarče *M* in pripadajočimi izračunanimi položaji *T*:

ware enables the identification of parameters that belong to the three submodels of the mechanism: the kinematic model, the actuator model and the model of elastic deformations [18]. The actuator model is composed of the actuators of the joints. RoboCal enables the modelling of closed kinematic chains within the individual actuators (crank-and-slider mechanism, parallelogram), whereas the kinematic model of the overall mechanism forms an open kinematic chain that starts at the base and ends at the flange (serial mechanism). Compared with this, the entity of the precision calibration apparatus and the CMA forms a closed kinematic chain (parallel mechanism). Consequently, there is no identification of the model of elastic deformations because the calculation of the load due to the dead weight of the links assumes that there is a free end to the kinematic chain.

3.1 Modelling

The two remaining submodels of the CMA are the kinematic model and the actuator model. The kinematic model is complete and comparable to the kinematic model of an articulated robot. Accordingly, the notion Ain-line wrist will be used to describe the entity of the last two axes of the CMA and the rotating vacuum-air bearing of the measurement device. The notation Atarget describes the location that the laser interferometer is aiming at. The actuator model describes the relation between the joint encoder reading and the angular position of the links relative to each other. The relation is described by the constant gear ratio plus a Fourier approximation describing the gear runout. For the above reasons (the calculation of load assumes a free end to the kinematic chain), there is no identification of the joint backlash. The selection of measurement poses belongs to the modelling, too. A pose pattern describes a dependency and thus may cover a similar dependency that is due to a model parameter. This redundancy causes rank deficiency of the model Jacobian. The elements of this matrix are the derivations of the target positions with respect to the model parameters. In a convenient way, redundancy can be detected and traced using the Singular Value Decomposition (SVD) of the model Jacobian.

3.2 Merit function

At each measurement pose *i*, the joint encoder values *h* of the CMA and the output of the laser interferometer are read. The calibration identifies the model parameters *p* that minimise the sum of all distances (i.e. Euclidean norms) that remain between each measured target position *M* and its corresponding computed position *T*:

$$\min_{p\in\Re^n}\left\{\left\|M-T\left(p,h\right)\right\|^2\right\}$$

3.3 Optimizacija modela

Metoda razstavitve po singularnih vrednostih (RSV) je bila uporabljena na modelnem Jacobianu ČKMN z uporabo različnih kompletov poz. Za razpoznavanje večine modelnih parametrov sta potrebni vsaj dve različni postavitvi kalibracijske naprave glede na merilno napravo CMA. Rezultati, ki so prikazani na naslednjih slikah, so dobljeni iz meritev v dveh različnih legah: pri prvi legi je kalibracijska naprava postavljena vodoravno, v drugi legi pa je kalibracijska priprava nagnjena za kot, ki znaša okoli 50° relativno glede na prvotno vodoravno lego. Parametri lahko postanejo medsebojno odvisni zaradi izbire mernih poz. Informacija meritve je tridimenzionalna. Poleg interferometrskih razdalj vzdolž osi merjenja lahko določimo tudi premike pravokotno na os merjenja. V primerjavi s pričakovano natančnostjo merilne naprave CMA so te vrednosti zanemarljivo majhne. Za izboljšanje natančnosti poze ta informacija zadostuje. V nasprotnem primeru obstaja možnost, da iz kalibracijske naprave razberemo petdimenzionalno merilno informacijo (zanemarimo vrednosti rotacije pravokotno na rotacijsko os vakuumsko prednapetega zračnega ležaja). Z uporabo tridimenzionalne informacije, se izkaže, da sta dva kinematična parametra v zaporedju od tretjega k četrtemu členku izrazito odvisna od preostalih kinematičnih parametrov in ju v razpoznavi ni. Če pogledamo še parametre pogona, vidimo, da majhen kot rotacije posameznih členkov pomikov povzroči koeficient sinusa pri Fourierjevi aproksimaciji, ki je odvisen od prestavnega razmerja.

3.3 Model optimization

SVD was applied to the model Jacobian of the CMA using different pose sets. At least two different configurations of the calibration apparatus with respect to the CMA are necessary in order to identify most of the model parameters. The results presented here are based on two configurations: in the first configuration, the calibration apparatus is oriented horizontally, and in the second configuration it is inclined by about 50 degrees relative to the previous position. Parameters may become dependent on each other due to the measurement set-up. The measurement information is three-dimensional. Not only is the displacement along the axis of the measurement device determined, the displacements orthogonal to this axis are also known to be negligible, compared to the expected pose accuracy of the CMA. For pose accuracy improvement, this information is sufficient. Otherwise, the calibration apparatus has the potential to serve for five-dimensional measurement information (negligible rotations orthogonal to the axis of the rotating vacuum-air bearing). With 3D information, two kinematic parameters in the sequence from the third to the fourth joint strongly depend on other kinematic parameters and thus are absent from a reliable identification. Concerning the actuator parameters, the small rate of joint movement makes the sine-coefficient of the Fourier approximation dependent on the gear ratio.

```
     |                                                          25 %
     |                                                           |
 2.1-|
     |000000000000000000000000X 10.3
2.34-|
     |
2.58-|
     |000000000000000000000000X 10.3
2.81-|
     |0000000X  3.4
3.05-|
     |00000000000000000000000000000000X 13.8
3.29-|
     |000000000000000000000000X 10.3
3.52-|
     |00000000000000000000000000000000X 13.8
3.76-|
     |000000000000000000000000000000000000000000000000000000000X 24.1
   4-|
     |00000000000000000000000000000000X 13.8
4.23-|
```

Sl. 8. *Porazdelitev rezultatov pred kalibriranjem v vodoravni legi*
(srednja vrednost: 3,4mm, standardno odstopanje: 0,59mm, največja razlika: 4,0mm)
Fig. 8. *Distribution of residuals prior to calibration in horizontal position*
(mean: 3.4mm, standard deviation: 0.59mm, maximum: 4.0mm)

```
     |                                                          25 %
     |                                                           |
 1.1-|
     |00000000000000000000000000000000X 13.8
1.26-|
     |0000000000000000X  6.9
1.43-|
     |0000000000000000X  6.9
1.59-|
     |0000000000000000X  6.9
1.75-|
     |0000000000000000000000000000000000000000X 17.2
1.91-|
     |00000000000000000000000000000000X 13.8
2.07-|
     |00000000000000000000000000000000X 13.8
2.23-|
     |0000000000000000000000000000000000000000000000000X 20.7
2.39-|
```

Sl. 9. *Porazdelitev rezultatov pred kalibriranjem v nagnjeni legi*
(srednja vrednost: 1,8mm, standardno odstopanje: 0,40mm, največja razlika: 2,3mm)
Fig. 9. *Distribution of residuals prior to calibration in inclined position*
(mean: 1.8mm, standard deviation: 0.40mm, maximum: 2.3mm)

```
       |                                                          25 %
       |                                                           |
0.0082-|
       |0000000000000000X  6.9
0.0111-|
       |
 0.014-|
       |000000000000000000000000X 10.3
0.0168-|
       |000000000000000000000000X 10.3
0.0197-|
       |0000000000000000000000000000000000000000X 17.2
0.0226-|
       |000000000000000000000000X 10.3
0.0255-|
       |00000000000000000000000000000000000000000000000000000000000| 27.6
0.0284-|
       |0000000X  3.4
0.0313-|
       |0000000X  3.4
0.0341-|
       |0000000X  3.4
 0.037-|
       |0000000000000000X  6.9
0.0399-|
```

Sl. 10. *Porazdelitev rezultatov po kalibriranju v vodoravni legi*
(srednja vrednost: 0,024mm, standardno odstopanje: 0,0072mm, največja razlika: 0,040mm)
Fig. 10. *Distribution of residuals after calibration in horizontal position*
(mean: 0.024mm, standard deviation: 0.0072mm, max: 0.040mm)

```
        |                                                          25 %
        |                                                           |
0.00923-|
        |0000000X  3.4
 0.0178-|
        |0000000X  3.4
 0.0264-|
        |000000000000000000000000000000000000000000000000000000000X 24.1
  0.035-|
        |0000000000000000000000000000000000000000X 17.2
 0.0436-|
        |00000000000000000000000000000000X 13.8
 0.0522-|
        |0000000000000000000000000000000000000000X 17.2
 0.0608-|
        |0000000000000000X  6.9
 0.0693-|
        |0000000X  3.4
 0.0779-|
        |
 0.0865-|
        |0000000000000000X  6.9
 0.0951-|
        |0000000X  3.4
  0.104-|
```

Sl. 11. *Porazdelitev rezultatov po kalibriranju v nagnjeni legi*
(srednja vrednost: 0,048mm, standardno odstopanje: 0,021mm, največja razlika: 0,10mm)
Fig. 11. *Distribution of residuals after calibration in inclined position*
(mean: 0.048mm, standard deviation: 0.021mm, max: 0.10mm)

3.4 Rezultati

Rezultati razpoznavanja kinematičnih parametrov so prikazani na slikah 8 do 11. Kakovost identifikacije parametrov razberemo iz statistične analize razlik, to je analize razlik med merjenimi in izračunanimi položaji tarče. To je postopek po IRIS-DIS 9283 [19]. S slik 8 in 9 sta razvidni porazdelitvi razlik pred kalibriranjem glede na lego kalibriranja. Tako slika 7 kaže rezultate merilne naprave v vodoravni legi in slika 9 pri nagibu 50^{o}. V vodoravni legi znaša največja razlika okoli 4 mm in je skoraj dvakrat večja kakor v nagnjeni legi. Porazdelitev razlik po kalibriranju prikazujeta sliki 10 in 11. V vodoravni legi znaša največja razlika okoli 0,04 mm. S tem je izboljšava s kalibriranjem za faktor 100 očitna. V nagnjeni legi je uspešnost kalibriranja prav tako očitna, vendar le za faktor 20. Povsem jasno je, da je obremenitev segmentov v obeh primerih povsem različna. Iz tega lahko sklepamo, da je vzrok razlike v faktorjih posledica elastičnih deformacij.

4 PREVERJANJE

Z namenom, da potrdimo pravilnost rezultatov razpoznavanja kinematičnih parametrov, smo izvedli eksperimentalno preveritev na prototipu ročno vodene členkaste koordinatne merilne naprave z rotacijskimi osmi. V ta namen smo parametre razpoznavne na podlagi postopka kalibriranja vnesli v kinematični model prototipa ČKMN. Nato smo merilno napravo ponovno priključili na kalibracijsko napravo. Tokrat smo kalibracijsko napravo uporabili kot referenčni merilni sistem, s katerim smo testirali absolutno natančnost ČKMN na temelju meritev premosti v različnih legah in v različnih smereh v prostoru. Merilni postopek je bil zelo podoben postopku pri kalibracijskih meritvah. Meritve so bile izvedene pri štirih različnih nagibih. Pri vsakem nagibu je bila ČKMN postavljena različno glede na referenčni merilni sistem. S tem smo povečali število različnih poz merjenja. Poze so bile izbrane v drugih položajih kakor pri kalibracijskih meritvah. S tem smo zagotovili resničnost postopka preverjanja. Rezultati meritve preverjanja so prikazani na sliki 12. Oznake H, IN15, IN30 in IN50 pomenijo, da je bila naprava postavljena v vodoravno lego (H), nagnjeno za 15^{o} (IN15), 35^{o} (IN35) oziroma za 50^{o} (IN50). V vsaki legi smo spreminjali položaj merilne naprave CMA relativno glede na referenčni merilni sistem. Lege označene s P1, P2, P3,P4 in P5, ki smo jih dodali oznakam H, IN15, IN30 in IN50 pomenijo, da je bil bazni koordinatni sistem ČKMN v P1 oddaljen za okoli 500 mm od merilne točke na referenčnem merilnem sistemu. Oznaka P3 pomeni isto pozicijo

3.4 Results

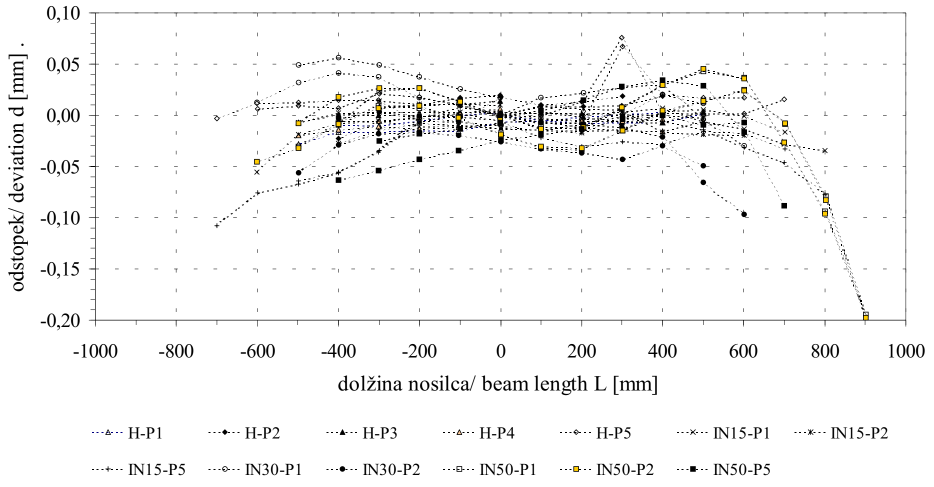
The results for the identification of the kinematic parameters are shown above. The quality of the parameter identification can be seen from the statistical analysis of the residuals, i.e. the analysis of the remaining differences between the measured and the calculated target positions. This is the procedure according to IRIS-DIS 9283 [19]. For both configurations, Figures 8 and 9 show the distribution of the residuals prior to calibration. Fig. 8 corresponds to the horizontal orientation of the measurement device and Fig. 9 to an inclination of about 50 degrees. In the former case, the maximum residuals are about 4mm and thus almost twice as large as in the latter one. The distribution of the residuals after calibration is shown in Figures 10 and 11. In the horizontal case, the maximum residuals are about 0.04mm. Thus calibration has improved this value by a factor of 100! In the inclined case, calibration decreases the maximum residuals by only a factor of 20. Obviously, the load distribution is different in the two cases, so elastic behaviour may be responsible for this observation.

4 VERIFICATION

To confirm the results of the identification of kinematic parameters we carried out experimental verification on a prototype of a manually driven coordinate measuring arm with exclusively rotational axes e.g. a CMA. For this purpose we put the parameters identified from the calibration procedure into the kinematic model of the existing prototype CMA and connected it to the high-precision calibration apparatus. In this case the high-precision calibration apparatus was used as a reference measuring system to check the absolute accuracy of the CMA on the basis of straightness measurements oriented in various spatial directions. The measuring procedure was very similar to the procedure in the calibration measurement. The measurements were made in four different inclinations. In each inclination the CMA was placed differently in relation to the reference measuring system to expand the variability of poses. The measuring poses were chosen a little bit differently from the calibration poses to ensure a credible verification procedure over the desired measuring area of the CMA. The results of this verification measurement are presented in Fig. 12. Notations: H, IN15, IN30 and IN50 mean that the reference measuring system was placed into the horizontal level (H), and then inclined for about 15 degrees (IN15), 35 degrees (IN35) and finally by 50 degrees (IN50). At each level we changed the position of the CMA relative to the reference measuring system. Positions marked by P1, P2, P3, P4 and P5, which were added to the previous denotations H, IN15, IN30 and IN50, mean that the base coordinate system of the CMA was initially positioned about 500 mm from the measuring point on the reference measuring system

ČKMN, le da je bila prva os zasukana za okoli 45° in oznaka P4 pozicijo, zasukano okoli prve osi za 45° relativno glede na referenčni merilni sistem. Oznaki P2 in P5 pomenita meritve v legi, ki je bila oddaljena 730 mm oziroma 400 mm od merilne točke na referenčnem merilnem sistemu. Te oznake veljajo pri vseh nagibih. Rezultati meritev, izvedenih na prototipu ČKMN, ki jih prikazuje slika 12, zajemajo rezultate, ki upoštevajo samo izboljšavo na podlagi kinematičnih parametrov.

(P1). Notation P3 represents the same position of the CMA where the first axis was turned by about +45 degrees and P4 the position turned by about 45 degrees relative to the reference measuring system. The notations P2 and P5 represent measurements in positions which were first 730 mm and secondly 400 mm away from the measuring point on the reference measuring system. The notation is valid for all measuring inclinations. Additionally, we should mention that the result of experiments carried out on a prototype of the CMA presented in Fig. 12 includes only kinematic parameters.



Sl. 12. *Rezultati natančnosti razdalje, ki so bili izvedeni na prototipu ČKMN, kalibrirane s programskim paketom RoboCal in merjenem na zelo natančni kalibracijski pripravi, ki je bila uporabljena tudi kot referenčni merilni sistem za testiranje absolutne natančnosti ČKMN na podlagi meritev natančnosti razdalje.*

Fig. 12. *Results for distance accuracy carried out on a prototype of the CMA calibrated with RoboCal software and measured on a high-precision calibration apparatus which was also used as a reference measuring system to check the absolute accuracy of the CMA on the basis of distance accuracy measurements.*

Pri ekstremno stegnjeni konfiguraciji mehanizma so razvidna odstopanja v navpični smeri (sl. 12). Ta odstopanja se ujemajo s teoretično predpostavko o vplivu elastičnih deformacij. Enako opažanje je razvidno pri meritvi, označeni s H-P5 pri +300 mm. V tej legi sta bili zadnji osi orientacijskega dela ČKMN v singularnem položaju. Odstopanja v tej poziciji so povezana z notranjimi silami in momenti, povezanimi s singularnim položajem in imajo za posledico elastično deformiranje konstrukcije.

5 SKLEP

Rezultati kalibriranja in njihovo preverjanje so pokazali, da z razvito kalibracijsko pripravo in s predlaganim postopkom lahko izvedemo zelo natančno kalibriranje členkastih koordinatnih merilnih naprav na podlagi meritev vzdolž ravne črte, nastavljive v različnih

From Fig. 12, in the extremely stretched arm configuration, noticeable deviations in the vertical direction were apparent, which confirm the theoretical supposition of the influence of elastic behavior. The same observation was also evident in the measurement marked with H-P5 at +300 mm. In this position the last two axes of the orientational part of the CMA were found to be in a singularity, where deviations in position as a consequence of elastic structural deformations caused by internal forces and moments occurred.

5 CONCLUSION

The calibration results and their verification show that the developed apparatus and proposed procedure can perform the calibration of CMAs with high precision on the basis of measurements along straight lines adjusted in prostorskih smereh. Izvedeno kalibriranje je izboljšalo natančnost poze ČKMN za faktor 100 (vodoravna postavitev) oziroma za faktor 20 (nagnjena postavitev). Na ta način je pokazano, da je mogoče absolutno natančnost členkastih koordinatnih merilnih naprav, namenjenih za geometrijska merjenja, uspešno izboljšati. Nadaljnje raziskave bodo najverjetneje ostredotočene na preučevanje elastičnih vplivov. Pri tem bomo iskali vzroke različnega obnašanja mehanizma pri vodoravnih in nagnjenih položajih. Prav tako je tudi vredno omeniti, da ni omejitev za uporabo kalibracijske priprave in postopka tudi za kalibriranje merilnih robotov z rotacijskimi osmi.

various spatial directions. The calibration performed improved the pose accuracy of the CMA by factors of 100 (horizontal position) or 20 (inclined position). In this way the absolute accuracy of CMAs intended for geometrical measurements can be successfully increased. In order to find the reason for the different behaviour in horizontal and inclined positions, further studies should concentrate on the elastic behaviour of the CMA. It is also worth mentioning that there are no limitations to the use of the apparatus and procedure for the calibration of measuring robots with rotational axes.

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