XIV MEĐUNARODNA NAUČNA KONFERENCIJA
INDUSTRIJSKI SISTEMI - IS'08
Oktobar 02-03, 2008, Novi Sad, Srbija

XIV INTERNATIONAL SCIENTIFIC CONFERENCE
INDUSTRIAL SYSTEMS - IS'08
October 02-03, 2008, Novi Sad, Serbia

Branislav Borovac[1]*, Milutin Nikolić*[1]

[1]*University of Novi Sad, Faculty of Technical Sciences*
21000-Novi Sad, Trg D, Obradovića 6, Serbia
borovac@uns.ns.ac.yu, ajsmilutin@gmail.com

O BIOLOŠKIM PRINCIPIMA ODRŽAVANJA DINAMIČKOG BALANSA POZE HUMANOID-NIH ROBOTA

Abstrakt

Osnovna karakteristika humanoidnih (dvonožnih) robota je zahtev za permanentnim održavanjem dinamičkog balansa. Dok su mali poremećaji stalno prisutni i njihova kompenzacija treba da se odvija ne narušavajući realizaciju nameravanog kretanja, veliki poremećaji su takvi da direktno ugrožavaju dinamički balans i prete padom sistema. Stoga kompenzacija ovih poremećajaja zahteva rayličite strategije. U radu se razmaraju načini kompenzacije velikih poremećaja čoveka pri očuvanju poze.

Ključne reči: *Humanoidni robot, ZMP, dinamički balans,veliki poremećaji, antropomorfizam*

1. UVOD

Već dugo roboti nisu samo prisutni u fabričkim halama, nihovom tradicionalnom radnom prostoruveć da su u većoj meri angažovani u bliskoj životnoj i radnoj okolini ljudi. To neminovno vodi ka “radnoj koegsistenciji” ljudi i robota i podeli zajedničkog „životnog i radnog prostora“. Obzirom da se ne može očekivati podešavanje čovekove okoline robotima kao nedvosmislen se nameće zaključak da će roboti morati da se prilagode u prostoru koji je u velikoj meri podešen čoveku. Okruženje u kome čovek živi i radi je u velikoj meri nestruktuirano. To znači da raspored i broj objekata u okviru prostora nije nepromenljiv, da se mogu dogoditi neplanirane situacije i da se uslovi okoline menjaju. Stoga je u velikoj meri logično da se pred robote koji deluju u takvoj okolini postavlja zahtev da robot treba uspešno da deluje u regularnom čovekovom okruženju na takav način da njegovo delovanje po efikasnosti bude što sličnije čovečijem. Jedan od apekata koje ovo pitanje uključuje je i antropomorfnost samog hoda.

Ovde postoje dva aspekta o kojima treba da se vodi

BIOLOGICAL PRINCIPLES OF PRESERVING DYNAMIC BALANCE OF HUMANOID ROBOT POSTURE

Abstract

Basic characteristics of humanoid (biped) robots is requirement for permanent preservation of dynamic balance. Smal perturbations are permanently present and their comepensation is performed without obstruction of walk already started. However, large perturbations directly endanger dynamic balance. Thus, compensation requires different strategies for each of those two cases. In this paper are studied comensation techniques humans performed to preserve posture under influence of large perturbations.

Key words: *Humanoid robots, ZMP, dynamic balance large perurbations, anthropomorphism*

1. INTRODUCTION

For a long time already, robots have not been present only in the industrial plants, their traditional workspace, but have been increasingly more engaged in the close living and working environment of humans. This fact inevitably leads to the need of “working coexistence” of man and robot and sharing their common working environment. The fact that no significant rearrangement of the humans' environment because of the presence of robots could be expected, robots will have to further “adapt” to the environment previously dedicated only to man. However, human environment is in large extent non-structured. i.e. number and disposition of objects is not fixed and that situation which are not expected can happen in the changing environment. Thus, robot have to act in the such environment in the way as much as possible, similar to humans. It is expected that the robots will have operation efficiency close to that of humans. One important question which have to be answered is walk anthropomorphism itself.There are two aspects that should be borne in mind. The first is, how to synthesize a gait with the highest possible degree of računa. Prvi je kako sintetizovati hod što većeg stepena antropomorfnosti. Drugi aspekt o kome treba voditi računa je kako očuvati antropomorfnost u prisustvu poremećaja, tj. kako realizovati što „antropomorfniju“ kompenzaciju poremećaja. Ovde se pre svega misli na način kompenzacije poremećaja koji treba da bude što prirodniji i „mekši” jer klasične metode automatskog upravljanja ovde ne daju adekvatne rezultate pošto isuviše „trzaju” sistem koji vezu sa okolinom ostvaruje jedino putem stopala koje je slobodno oslonjeno na podlogu. Stoga se u slučaju „grubih” kompenzacionih pokreta generišu neželjene inercijalne sile i preti opasnost od prevrtanja oko ivice stopala. Pored toga treba voditi računa o mogućnosti „raspodeljene” kompenzacije istog poremećaja sa više zglobova, tj. da se jedan poremećaj kompenzuje sa više zglobova istovremeno.

U ovom radu ćemo pokušati da doprinesemo odgovorima na ova pitanja.

2. O DINAMIČKOM BALANSU

Osnovni zadatak humanoida pri dvonožnom kretanju je da održava hod, tj. da spreči pad sistema. Drugačije rečeno, ukoliko želimo da sprečimo pad sistema dinamički balans humanoida mora biti neprestano održavan.

Tačka nula momenta (ZMP) [1-4], predstavlja glavni pokazatelj dinamičkog balansa. Ukoliko se uvede Dekartov koordinatni sistem sa početkom u tački u kojoj deluje rezultantna sila reakcije podloge, sa osama x i y tangentnim na podlogu i z osom normalnom na istu, onda je matematički uslov za ostvarivanje dinamičkog balansa:

$$\Sigma M_x = 0 \tag{1}$$

$$\Sigma M_y = 0 \tag{2}$$

Tačka unutar oslonačke površine (izuzimajući ivice) sa koju su zadovoljene jednačine (1) i (2) je ZMP. Neka se posmatra jednooslonačka faza hoda humanoida koji poseduje jednosegmentno stopalo. Donja strana stopala osnonačke noge je u kontaktu sa podlogom celom svojom provršinom, dok gornji deo humanida (deo iznad stopala) vrši kretanje. Dokle god pokreti humanoida ne izazivaju odvajanje stopala od podloge ZMP se nalazi unutar oslonačke površtine i sistem, kao celina, je dinamički balasiran.

Ovo važi i za dvosegmentno stopalo, stim da je kontakt između podloge i barem krajnjeg segmenta stopala (u ovom slučaju prstiju) regularan. Posmatrajmo četvorosegmentno obrnuto fizičko klatno oslonjeno na podlogu (Sl. 1). Zglobovi J^1, J^2 i J^3 su osnaženi. Ukoliko se segmenti L^2, L^3 i L^4 kreću tako da je segment L^1 nepokretan u odnosu na podlogu (Sl. 1a) sistem je dinamičkoj balansiran. Ali, ukoliko kretanje segmenata L^2, L^3 i L^4 uzrokuje da se L^1 odvoji od podloge (Sl. 1b), sistem neće biti u dinamičkoj ravno-

anthropomorphism, and second, how to preserve the synthesized gait anthropomorphism in the course of its realization in the presence of disturbances, i.e. how to realize “the most anthropomorphic” compensation of disturbances? This is primarily related to fact that compensatin of disturbances should be natural and "soft" as much as possible becuse methods of classical automatic control are too much "jerky" what is very inconvenient due to fact that only connection of the humanoid with the environment is by its feet and this contact with the ground is unilateral. Thus, in case of abrupt compensational movement such inertial forces can be generated which are able to overturn the system. Attention also should be focused on issue of disturbance "distributed compensation" i.e. compensation of one disturbance by more joints simultaneously.

In this paper we will try to offer some answers to these questions.

2. ABOUT DYNAMIC BALANCE

Maintenance of humanoid upright position i.e. to prevent system overturn is a humanoid's most important task. In other words, if we want to prevent humanoid's overturn dynamic balance should be permanently maintained.

Zero Moment Point (ZMP) [1-4], is basic indicator of dynamic balance. Consider a Cartesian frame at point where ground reaction force is acting with the x and y axes being tangential to the flat ground and the z axis being normal. Then, mathematical condition for fulfillment of dynamic balance is:

$$\Sigma M_x = 0 \tag{1}$$

$$\Sigma M_y = 0 \tag{2}$$

Point within supporting surface (excluding edges) where equations (1) and (2) hold is ZMP. Consider first a humanoid in a single-support standing posture having a one-link foot. The foot sole of the supporting leg is in static contact with the ground over its entire area while humanoids upper part (body part above foot) performs motion. While foot remains flat on the ground ZMP is within support area and system as a whole is dynamically balanced.

These considerations are valid for a two-link foot, too, where at least front link (representing the toes), should be flat on the ground. Consider the four-link physical inverted pendulum, supported on the ground by its bottom link (Fig. 1). The joints J^1, J^2, and J^3 are powered. If the links L^2, L^3, and L^4 move such that link L^1 remains immobile on the ground (Fig. 1a), then the system is dynamically balanced. If the motion of the links L^2, L^3, and L^4 causes L^1 to move and to lose contact with the ground the humanoid is not dy-

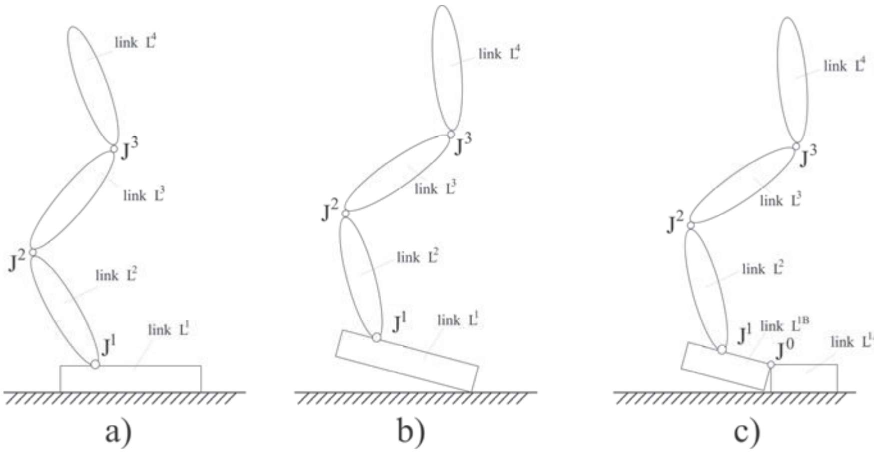


Fig 1. Ilustration of dynamic balabce notion

teži. Ako se segment L^1 sastoji od segmenata L^{1A} i L^{1B}, koji su povezanih zglobom J^0 i ako je zglob J^0 fiksiran segmenti L^{1A} i L^{1B} će se ponašati kao kruto telo. Ukoliko je zglob J^0 aktivan, sistem će biti u dinamičkoj ravnoteži samo ako je segment L^{1A} nepokretan na podlozi, (Sl. 1c). Segment L^{1B} se može kretati kao bilo koji drugi segment (L^2, L^3 i L^4), i on ne mora da bude u kontaktu sa podlogom.

Robot je u dinamičkoj ravnoteži ukoliko suma svih sila koje deluju na robota prodire podlogu u tački koja je unutar oslonačke površine. Međutim, ukoliko se desi da ZMP „izađe“ van oslonačke površine, biće generisan moment koji teži da prevrne robota oko ivice stopala. Međutim, mora da prođe određeno vreme, pre nego što pad postane neizbežan. U tom periou se može preduzeti odgovarajući kompenzacioni pokret da se pad spreči.

2. OPIS EKSPERIMENTA I MODELA

Volonteri koji su učestvovali u eksperimentu su bile tri zdrave odrasle osobe. Od svakog učesnika je traženo da se stojeći na levoj nozi levim ramenom nasloni na zid u koji je bio ugrađen pločasti senzor sile. Naslanjanje je trebalo nastaviti sve dok sila ne dostigne veličinu od 20 N. Ta sila približno odgovara položaju tels pri kom projekcija centra mase sistema na podlogu izlazi izvan oslonačke površine prekrivene stopalom oslonačke noge. Zid je zatim naglo uklonjen i kretanje subjekta je snimljeno. Svaki učesnik je eksprtiment ponovio deset puta i svi podaci su zabe-. leženi.

Ovaj eksperiment tokom kojeg su dobijeni podaci o kretanju subjekta je realizovan u Holodeck Gait Laboratory koja pripada Computer Science and Artificial Intelligence Lab at MIT, u studiji koja je odobrena od strane komiteta MIT-a za Odobravanje korišćenja ljudi kao subjekata u eksperimentima.

Procedura prikupljanja podataka je bila bazirana na standardnim tehnikama. Korišćene su infracrvene ka-

namically balanced. Let us assume the link L^1 consists of links L^{1A} and L^{1B}, connected via the joint J^0 (Fig. 1c). In the Figs. 1a and 1b, the joint J^0 is locked, so that the links L^{1A} and L^{1B} behave as a single body. If J^0 is also active, the system will be dynamically balanced only if L^{1A} remains immobile on the ground (Fig. 1c). The link L^{1B} may move like any other link (L^2, L^3 or L^4), and need not be in contact with the ground.

Thus, robot is in dynamic balance if at considered time instant sum of all acting forces penetrate ground surface at point which is within support area. But, if happen that ZMP "exit support area" perturbation moment will be generated to overturn robot about foot edge. But, this does not happen instantly. Certain time period is needed before fall become unavoidable. During this period compensation action can be performed aimed to prevent mechanism collapse.

2. EXPERIMENT AND MODEL

Three healthy adult participants volunteered for the study. For this pilot investigation, each participant was asked to stand on his left foot, and lean to his left until his shoulder touched a support. The support was a flat force sensor, and the participant was asked to lean until this sensor measured approximately 20 N of force. This level of force corresponded to a leaning posture where the CM projection on the ground surface fell outside the stance foot envelope. The support was then suddenly pulled away and motion recorded. For each study participant, a total of ten trials were collected

Kinematic and dynamic data were collected at the Holodeck Gait Laboratory of the Computer Science and Artificial Intelligence Lab at MIT, in a study approved by the MIT committee on the Use of Humans as Experimental Subjects.

The data collection procedures were based on standard techniques. An infrared camera system (VICON 512) was used to measure the three-dimensimere (VICON 512) da bi se merili trodimenzionalni položaji refleksivnih markera učestaniošću od 120 puta u sekundi. Ukupno je na jednom subjektu, na različitim delovima tela, bilo pričvršćeno 33 markera: šesnaest na donje ekstremitete, pet markera je bilo pričvršćeno na trup, osam na gornje ekstremitete i četiri na glavu. Sistem VICON 512 je bio u stanju da odredi položaj markera sa tačnošću od ~1 mm. Sinhrono sa kinematskim podacima su mereni podaci o sili reakcije podloge, isto sa učestanošću od 120 puta u sekundi pomoću platforme (Advanced Mechanical Technology Inc., Watertown, MA). Platformom su intenzitet i položaj sile reakcije su mereni tačnošću od ~0.1 N i ~2 mm, respektivno.

Položaj CM sistema je sračunat naknadno na osnovu snimljenih podataka. Položaj ZMP-a i intenzitet sile reakcije podloge je meren pomoću senzora sile.

Na Sl. 2 je prikazana kinematska shema mehaničke strukture robota koja je korišćena u ovom radu. Osnova na bazi koje je formiran model mehanizma je softver za formiranje dinamičkog modela razgranatog (otvorenog ili zatvorenog) kinematskog lanca čiji su segmenti spojerni zglobovima sa po jednim stepenom slobode

Mehanizam se oslanja o levu nogu. Prvi kinematski lanac predstavlja noge (segmenti 1-27), drugi se proteže od karlice i sadrži trup i desnu ruku (segmenti 61, 28, 29, 62, 30-42), treći lanac (segmenti 43-54) formira levo rame i ruku, dok četvrti lanac (segmenti 55-60) formira vrat u glavu (Fig. 2).

Zglobovi sa više stepeni slobode su modelovami kao skup "fiktivnih" segmenata (segmenati bez mase i nulte dužine) koji su spojeni zglobovima koji imaju jedan stepen slobode. Tako, na primer, kukovi, koji su u stvarnosti sferni zglobovi sa po tri stepena slobode su modelirani kao skup od tri, međusobno ortogonalna, zgloba sa po jednim stepenom slobode.

Prema tome, levi kuk je modeliran kao skup jednostrukih zglobova 13, 14 i 15 (čiji jedinični vektori osa rotacije su e_{13}, e_{14} i e_{15}), a desni skupom zglobova 16, 17 i 18 (jedinični vektori su e_{16}, e_{17} i e_{18}). Segmenti koji povezuju ove zglobove (za levi luk segmenti 13 i 14, a za desni kuk segmenti 16 i 17) su bili neophodni samo da se zadovolji matematički formalizam modeliranja kinematskog lanca. Drugi segmenti (koji nisu deo deo zglobova sa više stepeni slobode) i čije karakteristike odgovaraju segmentima prosečnog ljudskoh tela (segment 9 odgovara potkolenici, segment 12 butini itd) su na Sl. 2 prikazani punom linijom, dok su prethodno pomenuti "fiktivni" segmenti prikazani isprekidanim linijama.

Dinamički parametri mehanizma su su bili određeni tako da, u što je moguće većoj meri, odgovaraju stvarnim vrednostima parametara subjekta. Stopala i šake su modelirani kao paralelopipedi, segmenti nogu i ruku kao zarubljeni konusi. Mase, gustine i položaji

onal locations of reflective markers at 120 frames per second. A total of thirty-three markers were placed on various parts of a participant’s body: sixteen lower body markers, five trunk markers, eight upper limb markers, and four head markers. The VICON 512 system was able to detect marker position with a precision of ~1 mm. Ground reaction forces were measured synchronously with the kinematic data at a sampling rate of 120 Hz using a force platform (Advanced Mechanical Technology Inc., Watertown, MA). The platform’s ground reaction force and ZMP location were measured at a precision of ~0.1 N and ~2 mm, respectively.

Whole body CM position was computed after experiment from the kinematic data obtained in experiment. The ZMP, and the ground reaction force intensity were obtained from the force plate.

In Fig. 3 is shown the kinematic scheme of robot's mechanical structure that was used in the present work. The basis for deriving the mechanism’s mathematical model is the software for forming the dynamic model of a branched (open or closed) kinematic chain whose links are interconnected with joints having only one degree of freedom (DOF).

The mechanism is supported on the left leg. The first kinematic chain represents the legs (links 1-27), the second chain extends from the pelvis and comprises the trunk and the right arm (links 61, 28, 29, 62, 30-42), the third chain (links 43-54) forms the left shoulder and arm, and the fourth chain (links 55-60) forms the neck and head (Fig. 3**).**

The multi-DOF joints were modeled as a set of "fictitious" links (massless links of zero-length) interconnected with the joints having one DOF. For example, the hip joints, which are in reality spherical joints with three DOFs, are modeled as sets of three one- DOF joints whose axes are mutually orthogonal. Thus, the left hip is modeled by a set of simple joints 13, 14 and 15 (with the unit rotation axes vectors e_{13}, e_{14} and e_{15}), and the right hip by the set of joints 16, 17 and 18 (the unit vectors e_{16}, e_{17} and e_{18}). The links connecting these joints (for the left hip the links 13 and 14, and for the right hip links 16 and 17) were needed only to satisfy the mathematical formalism of modeling a kinematic chain. The other links (those that are not part of the joints with more DOFs) whose characteristics correspond to the links of an average human body (link 9 corresponds to the shank, link 12 to the thigh, etc.), are presented in Fig. 3 by solid lines. In the same figure, the above mentioned „fictitious“ links are represented by dashed lines.

The mechanism’s dynamic parameters were determined so to be as close as possible to those of the human experimental subject. The feet and hands were modeled as rectangular boxes. The shanks, thighs, forearms and upper arms were modeled as truncated

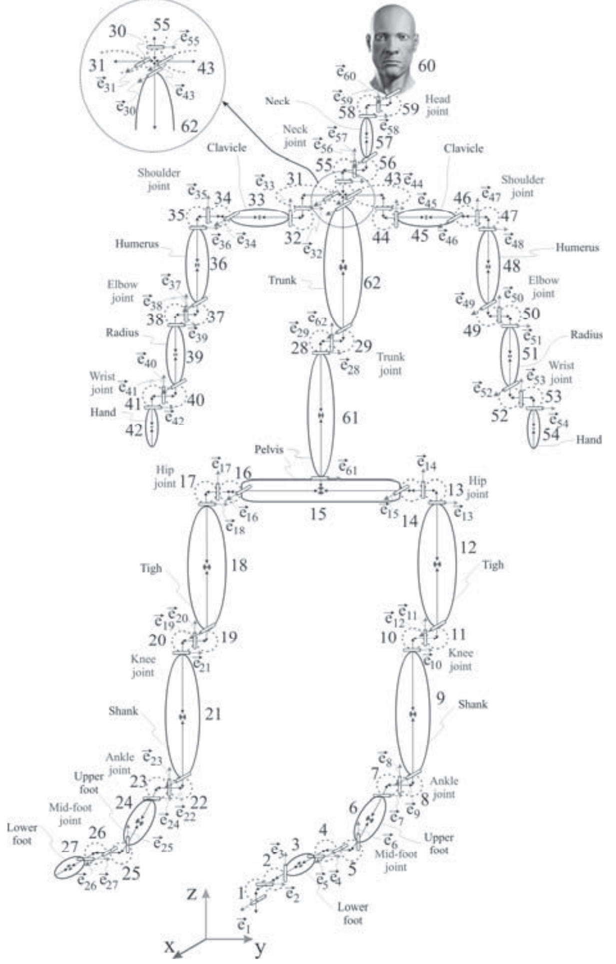


Fig. 2. Schematic of the robot's basic mechanical configuration having 62 DOFs

teñišta karlice, stomačnog dela i segmenta grudnog koša su bili modelovani tako da, što ke moguće i većoj meri odgovaraju eksperimentalnim podacima.

3. REZULTATI

U ovom poglavlju će biti predstavljeni rezultati eksperimenta tokom kojeg je čovek bio podvrgnut dejstvu velikih poremećaja, njegovo ponašanje je snimljeno (Sl. 3) a zatim je formiran model kojim je snimljeno kretanje ponovljeno. Modeliranje je izvršeno da bi bili u stanju da sračunamo sve potrebne karakteristike ponašanja subjekta koje nije bilo moguće identifikovati tokom eksperimenta.

Tokom eksperimenta čovek se, stojeći ne levoj nozi levim ramenom naslanja na zid. Sila kontakta ramena i zida se meri i kada dostigne 20 N zid se naglo izmiče. Usled gubitka oslonca u ramenu pojavljuje se opasnost od pada pa subjekt eksperimenta energičnim pokretom tela uspeva da sačuva ravnotežu i spreči pad. Ceo pokret, kao i intenzitet i položaj sile reakcije podloge ispod stopala oslonačke noge se snimaju. Početni trenutak od koga ćemo posmatrati ponašanje

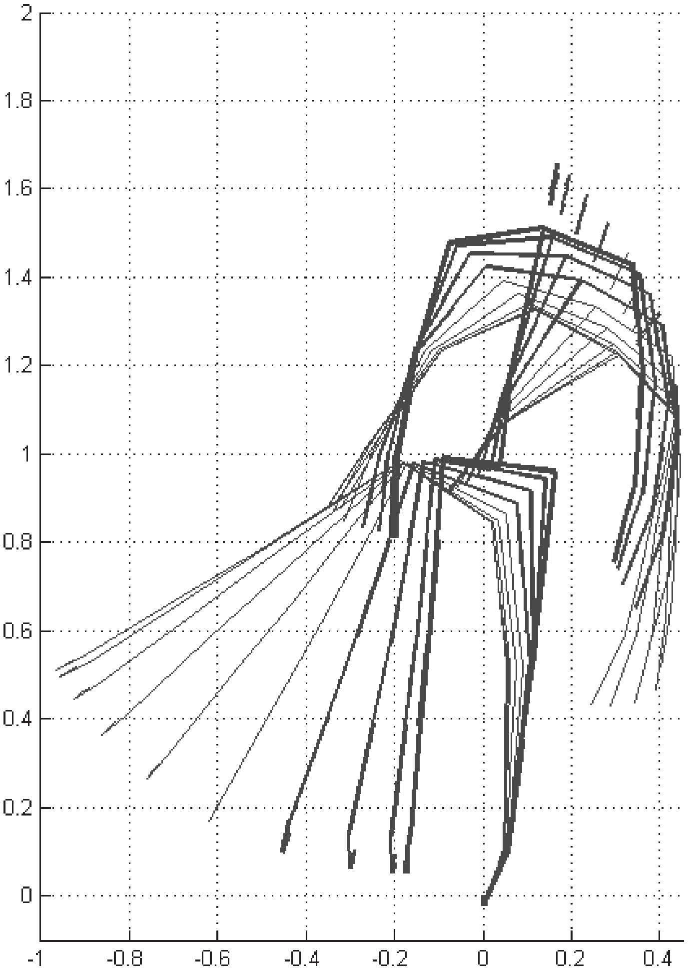


Fig 3. A sequence of subject's intermediate positions during experiment

cones. The pelvis-abdomen link and the thoracic link masses and densities and CM positions were modeled to closely match the experimental values.

3. RESULTS

In this section will be presented results of experiment where human subject was submitted to large perturbations. His motion was captured and recorded (Fig. 3). Model of humanoid was formed and than, recorded motion was repeated. Modelling was done to be able to calculate all relevant charactheristics of subject behaviour which was not possible to identify during experiment

In experiment, human subject standing on the left foot lean bz his left shoulder againt obstacle. Contact force between shoulder and obstacle was measured, and when reach 20 N obstacle is suddenly removed. Due to loss of support subject is in danger to fall down and by energetic movement he succeed to preserve balance and prevent collapse. Whole movement, as well as intensity and location of ground reaction force is recorded. Starting point for behaviour observation was

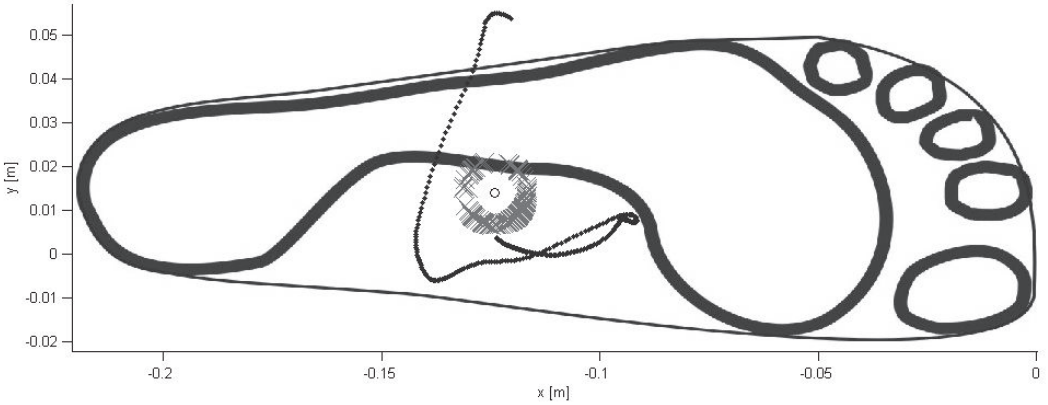
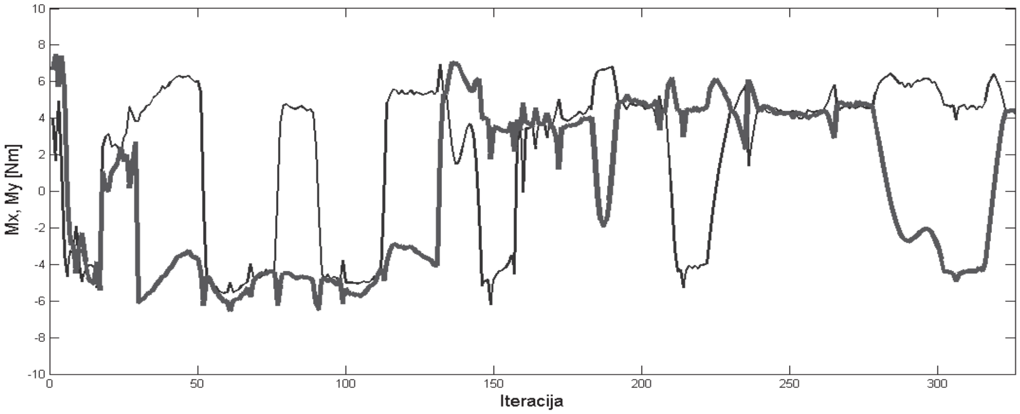


Fig. 4. Sketch of supporting foot area, ZMP trajectory (denoted by crosses) and CM projection trajectory (denoted by dots),



Slika 5 Calculated moment for reference ZMP position ($\Sigma\vec{M}_{ZMP}^{ref}$). Moment component on *x* axis is denoted by blue line, on *y* direction by red line

subjekta eksperimenta je deset iteracija, pre nestanka sile u ramenu koje nastaje zbog izmicanja vertikalnog zida. Za završni trenutak odabran je trenutak u kome se subjekt nakon energičnog kompenzacionog pokreta vrati u početnu pozu i umiri. Svi dijagrami koji slede su dobijeni iz modela koji je formiran na osnovu eksperimentalnih podataka.

Na Sl. 4. je prikazatn položaj ZMP-a i projekcija centra mase kompletnog sistema na oslonačku površinu tokom celokupnog posmatranog pokreta.

Da bi mogli date podatke da analiziramo i proverimo formiran je analitički model dinamičkog balansa humanoida proizvoljnog stepena složenosti . Ukoliko se sve unutrašnje koordinate, unutrašnje brzine i unutrašnja ubrzanja predstave u vektorskoj formi:

$q=(q_1 \dots q_n)^T$, $\dot{q}=(\dot{q}_1 \dots \dot{q}_n)^T$ i $\ddot{q}=(\ddot{q}_1 \dots \ddot{q}_n)^T$,

gde je *n* broj stepeni slobode sistema, traženi model se može napisati u sledećem obliku:

ten iterations before loss of shoulder contact force due to removing of vertical obstacle. As a final observation time instant was moment when, after energetic compensation motion subject return to initial position and settle down. All diagrams are obtained from model which is formed on the basis of data obtained from experiment.

In Fig. 4. is depicted ZMP position and vertical projection of complete system CM on ground surface during observed period.

To be able to analyze recorded data we formed analytical model of dynamic balance of humanoid robot having large number of degrees of freedom. If all joints coordinates, joint velocities and joint accelerations are given in form $q=(q_1 \dots q_n)^T$, $\dot{q}=(\dot{q}_1 \dots \dot{q}_n)^T$ i $\ddot{q}=(\ddot{q}_1 \dots \ddot{q}_n)^T$, where *n* represents number of system degrees of freedom, model can be written in the form

$$\Sigma\vec{M}_{ZMP} = \begin{pmatrix} 0 \\ 0 \\ M_z \end{pmatrix} = \vec{M}_G(q) + \vec{\Phi}(q)\ddot{q} + \vec{\phi}_0(q,\dot{q}) \qquad (3)$$

gde je sada matrica $\vec{\Phi}(q)$ dimenzija $3 \times n$, i može se prikazati u formi

$$\vec{\Phi}(q) = \left(\vec{\Phi}_1(q) \quad \ldots \quad \vec{\Phi}_i(q) \quad \ldots \quad \vec{\Phi}_n(q)\right) \qquad (4)$$

gde $\vec{\Phi}_i(q)$ predstavlja uticaj ubrzanja u *i*-tom zglobu na vektor ukupnog momenta u odnosu na ZMP. Vektor $\vec{M}_G(q)$ prestavlja ukupan momenat koji stvaraju gravitacione sile u odnosu na ZMP. Vektor $\vec{\phi}_0(q,\dot{q})$ predstavlja uticaj brzina na moment u odnosu na ZMP.

Najpre ćemo verifikovati ispravnost analitičkog modela tj. jednačine (3) tako što ćemo, koristeći podatke iz eksperimenta, odrediti sve njene članove i sabrati ih. Kao rezultat treba da se dobije trajektorija $\Sigma\vec{M}_{ZMP}^{ref}$ istovetna onoj koja je prikazana na Sl. 5. Članove jednačine (3) ćemo odrediti koristeći numerički model skiciran na Sl 2 na sledeći način:

Procedura se sastoji od 5 koraka. Tokom svih koraka ćemo koristiti podatke snimljene tokom eksperimenta stim da ćemo, da bi eliminisali neke od efekata, odgovarajuće veličine u tom koraku stavljati da su jednake nuli. Tokom svih 5 koraka uglovi nikada nisu bili postavljeni na nulu i oni su uvek imali vrednosti koje su snimljene tokom eksperimenta. U tekstu koji sledi detaljno je opisan svaki korak:

1. Najpre ćemo odrediti doprinos gravitacionih sila momentu $\Sigma\vec{M}_{ZMP}$ tj. odredićemo član $\vec{M}_G(q)$ jednačine (3) Da bi to uradili, modifikovaćemo ulazne podatke na sledeći način: promena uglova $q(t)$ u svim zglobovima tokom posmatranog pokreta ostaje identična snimljenim vrednostima tokom eksperimenta, ali, tokom celog pokreta u svim zglobovima vrednosti brzina i ubrzanja će biti postavljene na nulu i na taj način ćemo odrediti član $\vec{M}_G(q)$.

Sledeći član koji treba da odredimo je $\vec{\Phi}(q)\ddot{q}$ (tj. uticaj ubrzanja) i to ćemo uraditi iz tri koraka:

2. I u ovom slučaju će promena uglova $q(t)$ u svim zglobovima tokom posmatranog pokreta ostati identična snimljenim vrednostima tokom eksperimenta. Vrednosti brzina $\dot{q}(t)$ su u svim zglobovima su postavljene na nulu, dok su vrednosti ubrzanja u svim zglobovima, osim u skočnom zglobu, takođe postavljene na nulu. Kada je tokom celog pokreta sračunata vrednost

$$\Sigma\vec{M}_{ZMP} = \begin{pmatrix} 0 \\ 0 \\ M_z \end{pmatrix} = \vec{M}_G(q) + \vec{\Phi}(q)\ddot{q} + \vec{\phi}_0(q,\dot{q}) \qquad (3)$$

where matrix $\vec{\Phi}(q)$ of dimensions $3 \times n$, and can be written in form

$$\vec{\Phi}(q) = \left(\vec{\Phi}_1(q) \quad \ldots \quad \vec{\Phi}_i(q) \quad \ldots \quad \vec{\Phi}_n(q)\right) \qquad (4)$$

where $\vec{\Phi}_i(q)$ represents influence of acceleration on in *i*-th joint on moment with respect of ZMP. Vector $\vec{M}_G(q)$ represents total moment produced by gravitational forces with respect to ZMP Vector $\vec{\phi}_0(q,\dot{q})$ represents velocities influence on moment with respect to ZMP

Let us first verify correctness of analytical model i.e. equation (3) in such a way that we will use from experiment reordered data determine all members of (3) and sum them. As result we should obtain same trajectory of $\Sigma\vec{M}_{ZMP}^{ref}$ as presented on Fig. 5. Members of equation (3) will be determined using numerical model sketched in Fig. 2 in following way:

Procedure consists of five steps. In all steps we will use data reordered during experiment in such a way that we will eliminate certain effects by setting in this step corresponding values of data to zero. During all procedure angles were never set to zero, and always were used angle data exactly as recorded during experiment. In text which follows are described in details all steps.

1. Let us first determine contribution of gravitational forces to moment $\Sigma\vec{M}_{ZMP}$ i.e. we will determine term $\vec{M}_G(q)$ of (3). To achieve this we will modify data in folowing way: recordered angles $q(t)$ during experiment will remain unchanged for complete movement. However, during complete movements all velocities and accelerations will be set to zero. As a result, term $\vec{M}_G(q)$ will be determined.

Next term which should be determined is $\vec{\Phi}(q)\ddot{q}$ i.e. influence of acceleration. This will be done in three steps.

2. In this case recordered angles $q(t)$ during experiment will not be changed and will be identical to data captured during experiment. All joints velocities $\dot{q}(t)$ are also set to zero, while accelerations in all joints except in ankle joint of supporting leg are also set to zero. When, after such settings, $\Sigma\vec{M}_{ZMP}$ is determined over all movement, we, in fact,

$\Sigma\vec{M}_{ZMP}$ ustvari je određen zbirni uticaj ubrzanja u skočnom zglobu i gravitacije tj. odredili smo $\vec{\Phi}^{skocni}(q)\ddot{q}^{skocni} + \vec{M}_G(q)$.

3. U ovom koraku je u potpunosti ponovljena procedura iz prethodnog koraka (promena uglova $q(t)$ u svim zglobovima tokom posmatranog pokreta je. identična snimljenim vrednostima tokom eksperimenta, dok je $\dot{q}(t)$ u svim zglobovima postavljeno na nulu) osim što su u ovom slučaju ubrzanja jednaka nuli u svim zglobovima <u>osim u zglobu kuka</u>. Na taj način je u ovom koraku određen zbirni uticaj ubrzanja u kuku i gravitacije, tj. $\vec{\Phi}^{kuk}(q)\ddot{q}^{kuk} + \vec{M}_G(q)$.
4. I u ovom koraku promena uglova svim zglobovima $q(t)$ odgovara snimljenim vrednostima tokom eksperimenta, dok su brzine $\dot{q}(t)$ u svim zglobovima postavljene na nulu. <u>Ubrzanja u svim zglobovima odgovaraju snimljenim vrednostima</u> tokom eksperimenta, <u>osim u skočnom zglobu i kuku</u>. Na taj način je određen preostali deo člana $\vec{\Phi}(q)\ddot{q}$ tj. dobijeni su doprinosi ukupnom momentu $\Sigma\vec{M}_{ZMP}$ usled ubrzanja u svim zglobovima osim usled ubrzanja u skočnom zglobu i kuku. Naravno, i u ovom slučaju su gravitacioni efekti bili uključeni.

Kada saberemo vrednosti za $\Sigma\vec{M}_{ZMP}$ dobijene u koracima 2, 3 i 4 i oduzmemo tri puta momente usled gravitacionih efekata dobićemo vrednost člana $\vec{\Phi}(q)\ddot{q}$ iz jednačine (3).

5. I na kraju, treba odrediti uticaj brzina. I u ovom slučaju promena uglova svim zglobovima odgovara snimljenim vrednostima tokom eksperimenta, dok su vrednosti ubrzanja u svim zglobovima postavljene na nulu. Na taj način smo dobili sumarni uticaj brzina i gravitacije. Ako se oduzmu momenti usled gravitacionih sila dobićemo treći član jednačine (3), tj. $\vec{\phi}_0(q,\dot{q})$.

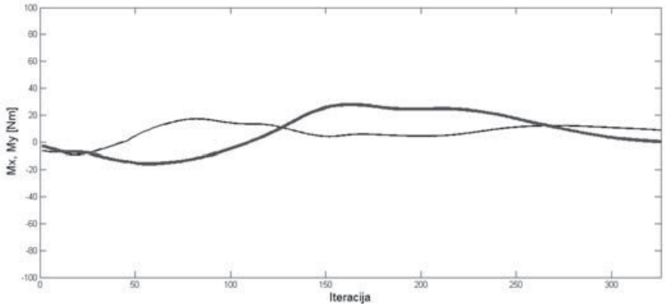


Fig 3 6 – $\Sigma\vec{M}_{ZMP}$ due to gravitational forces. *x* axis direction – blue line, *y* axis direction – red line

obtained overall influence of acceleration in ankle joint and gravitation. In other words, term $\vec{\Phi}^{skocni}(q)\ddot{q}^{skocni} + \vec{M}_G(q)$ was determined.

3. In this step is completely repeated procedure from previous step (recordered angles $q(t)$ during considered movement were not changed and were identical to data captured during experiment, while angular velocities $\dot{q}(t)$ in all joints were set to zero). In this case accelerations in all joints were also set to zero except in hip angle . In this way in this step is determined mutual influence of acceleration in hip and gravitation, i.e. $\vec{\Phi}^{kuk}(q)\ddot{q}^{kuk} + \vec{M}_G(q)$.
4. In this step too, recordered angles $q(t)$ during considered movement were not changed and were identical to data captured during experiment, while angular velocities $\dot{q}(t)$ in all joints were set to zero. <u>Accelerations in all joints corresponds to recordered values</u> during experiment , <u>except in ankle and hip</u> of supporting leg. In this way is determined remining term $\vec{\Phi}(q)\ddot{q}$ i.e. contributions of accelerations in all joints to $\Sigma\vec{M}_{ZMP}$, except hip and ankle are determined. Of course, in this case, too, acceletation effect were included in obtainined value of $\Sigma\vec{M}_{ZMP}$.

When values for $\Sigma\vec{M}_{ZMP}$ obtained in steps 2, 3 and 4 are summed and if we substract three times gravity effects term $\vec{\Phi}(q)\ddot{q}$ from equation (3) will be determined.

5. On the end, influence of velocities have to be deternined. In this case, too, recordered angles $q(t)$ and velocities $\dot{q}(t)$ during considered movement were not changed and were identical to data captured during experiment, while angular accelerations $\ddot{q}$ in all joints were set to zero. After subtracting influence of gravitation term. $\vec{\phi}_0(q,\dot{q})$ will be determined.

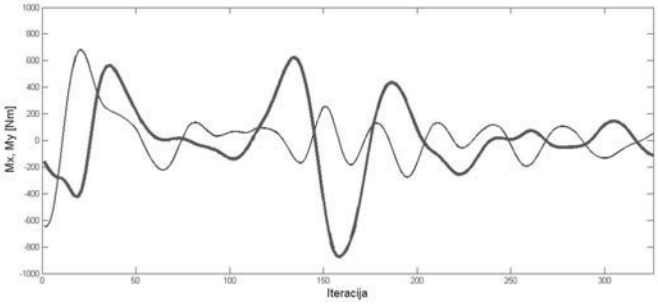


Fig 4 7 – $\Sigma\vec{M}_{ZMP}$ due ankle acceleration of supporting leg *x* axis direction – blue line, *y* axis direction – red line

Na narednim slikama će, u vidu dijagrama, biti prikazane sračunate veličine na prethodno opisani način. Na Sl. 6 je prikazan moment gravitacionih sila za referentni položaj ZMP-a, na Sl. 7 i 8 momenti sila indukovanih ubrzanjem u skočnim zglobu i kuku, respektivno. Sl. 9 je prikazan moment sila za referentni položaj ZMP-a usled ubrzanja svih ostalih zglobova, a na Sl. 10 moment sila usled brzinskih efekata. Kada se svi ovi momenti saberu jasno se vidi da se uticaji međusobno anuliraju (Sl. 11). Sada je trebalo utvrditi kretanja kojih zglobova poništavanju međusobne uticaje usled kompenzacionih pokreta. Očekivali smo da se efekti usled ubrzanja i skočnom zglobu i kuku u velikoj meri poništavaju pa je na Sl. 12 prikazana njihova suma. Kao što se može videti do poništavanja ne dolazi pa je ostalo da se utvrdi kretanja u kojim zglobovima poništavaju efekte ovih ubrzanja

Pažljivim pregledom eksperimentalnih podataka primetili smo da postoji registrovano kretanje između segmenata prstiju i podloge. Obzirom da prsti treba da

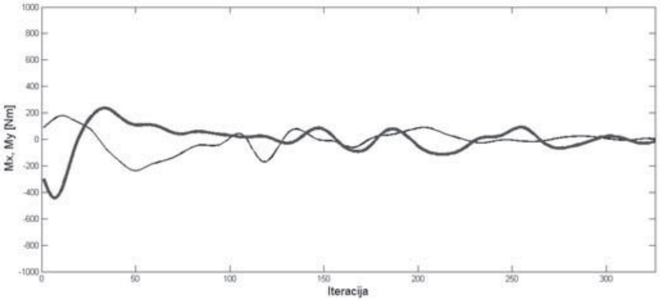


Fig. 5 8 – $\Sigma\vec{M}_{ZMP}$ due hip acceleration of supporting leg. *x* axis direction – blue line, *y* axis direction – red line

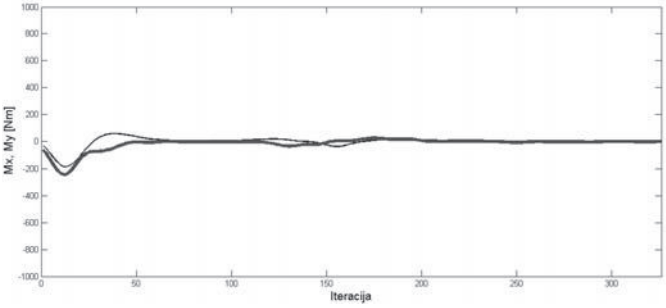


Fig. 7 10 – $\Sigma\vec{M}_{ZMP}$ due velocities influence. *x* axis direction – blue line, *y* axis direction – red line

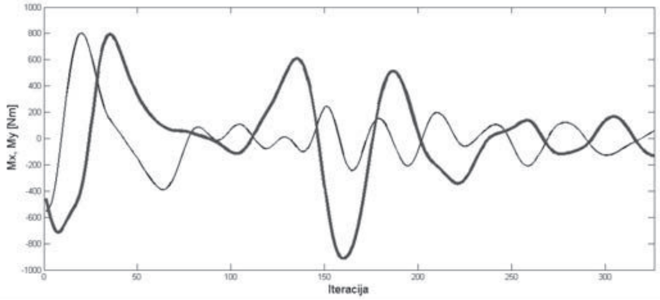


Fig. 9 12 – $\Sigma\vec{M}_{ZMP}$ due ankle and hip acceleration of supporting leg . *x* axis direction – blue line, *y* axis direction – red line

In following figures will be, in form of diagrams, presented values computed on already described way. In Fig. 6 is shown diagram of gravitational moments computed for reference ZMP. In Figs. 7 and 8 are shown moment of forces induced by acceleration in ankle and hip, respectively. In Fig. 9 is shown moment due acceleration in all other joints, while in Fig. 10 is shown moment due velocities in all joints. When all mentioned moments are summed it is clear that all effect are cancelled (Fig. 11). Now, it has to be determined which joints motions mutually cancel effects induced by compensation. We expected that effects due acceleration in ankle and hip joints are in large extent mutually cancelled, and in Fig. 12 is presented their sum. As can be seen cancellation did not happen, and it have to be determined what cancel motions effects of those two joints.

By careful examination of experimental data we noticed that motion between fingers and ground was recorded. Because fingers should be immobile on the

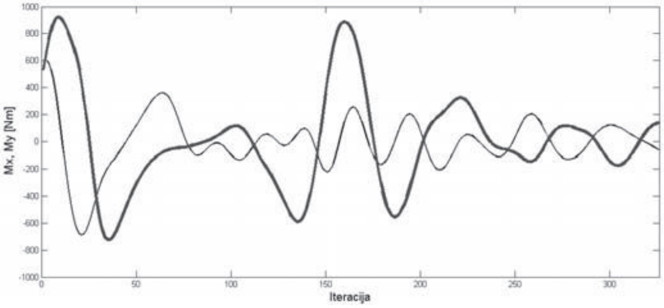


Fig. 6 9 – $\Sigma\vec{M}_{ZMP}$ due acceleration of all supporting leg joints except ankle and hip. *x* axis direction – blue line, *y* axis direction – red line

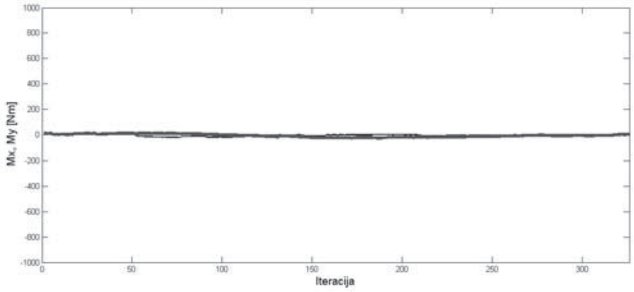


Fig. 11 11 – $\Sigma\vec{M}_{ZMP}$ due ankle and hip acceleration of supporting leg and of all other joints except ankle and hip plus velocities influence. *x* axis direction – blue line, *y* axis direction – red line

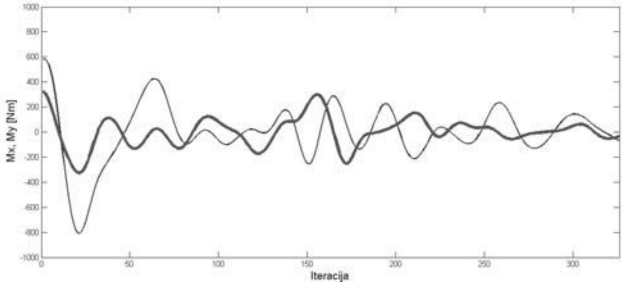


Fig. 10 13 – $\Sigma\vec{M}_{ZMP}$ due acceleration produced by motion between fingers segment and ground surface. *x* axis direction – blue line, *y* axis direction – red line

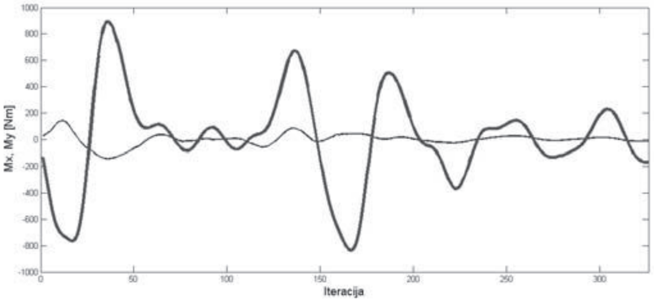


Fig. 13 14 – $\Sigma\vec{M}_{ZMP}$ due acceleration produced by motion between fingers segment and ground plus acceleration effect of ankle and hip of supporting leg. *x* axis direction – blue line, *y* axis direction – red line

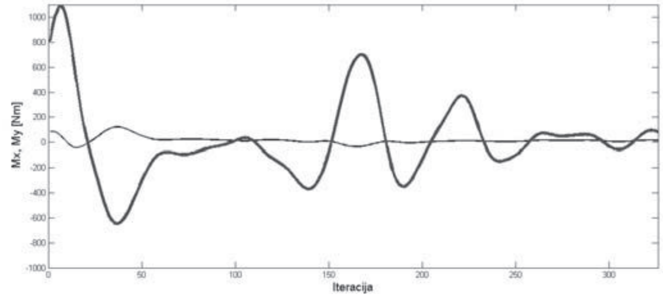


Fig. 15 16 – $\Sigma\vec{M}_{ZMP}$ due acceleration produced by knee motion of supporting leg. *x* axis direction – blue line, *y* axis direction – red line

stoje nepokretno na podlozi ta kretanja su mogla biti samo posledica elastičnih deformacija mekog tkiva na prstima. Sračunali smo efekte ovih kretanja i dobili dijagram prikazan na Sl. 13. Dodavanjem ovih momenata na momente generisane kretanjem skočnog zgloba i kuka dobijen je dijagram prikazan na Sl 14. Očigledno je da su ova kretanja poništila efekte u *x* pravcu. U *y* pravcu su na oslonačkoj nozi aktivni još zglob između segmenata prstiju i stopala i koleno. Na Sl. 15 i 16 su prikazani momenti generisani usled ovih kretanja, , a na Sl. 17 njihova suma.Vidi se da su efekti u velikoj meri poništeni i da kada se dodaju efekti brzina (Sl. 10) ponovo se stiže do dijagrama sa Sl. 11.

5. ZAKLJUČAK

U ovom radu smo se bavili održavanjem dinamičkog balansa poze čoveka u prisustvu velikih poremećaja. Zaključeno je da kretanja u skočnom zglobu i kuku "privlače" težište sistema u okvir oslonačke površinekako bi posle kompenzacije sistem ostao u dinamičkoj ravnoteži, a od izuzetnog značaja je fleksibilnost stopala koje omogućava da da je tokom tog procesa sistem ostane u dinamičkoj ravnoteži.

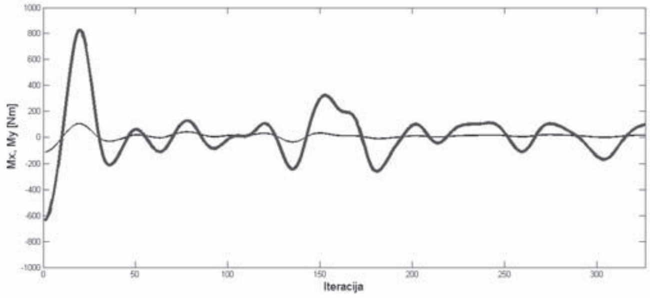


Fig. 14 15 – $\Sigma\vec{M}_{ZMP}$ due acceleration produced by motion between fingers and foot of supporting leg. *x* axis direction – blue line, *y* axis direction – red line

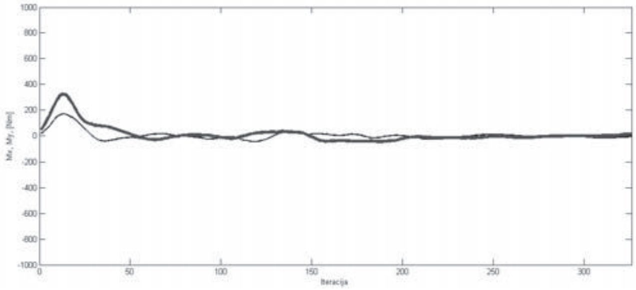


Fig. 16 17 – $\Sigma\vec{M}_{ZMP}$ due acceleration produced by knee motion of supporting leg. *x* axis direction – blue line, *y* axis direction – red line

ground, this motion can only be a consequence of elastic deformations of finger's soft tissue. We calculated effects of these motions and obtained diagrams presented in Fig. 13. By adding those moments on moments generated by ankle and hip motion Fig. 14 was obtained. It is obvious that motions due fingers elastic deformations cancelled motions in *x* direction. In *y* direction remained active joint between fingers and foot and knee. In Figs. 15 and 16 are shown moments generated by these motions, while in Fig. 17 is shown their sum. It can be seen that effects are at large extent canceled, and if we add moments caused by velocities (Fig. 10) we come again to diagrams of complete cancellation (Fig. 11).

5. CONCLUSION

In this paper we investigated preservation of dynamic balance of humans under influence of large perturbations. We consluded that anle and hip motions bring CM of complete system inside support area to enable that system remain balanced after compensationa is completed, while foot flexinilitu enable that during this process system remain in dynamic balance.

REFERENCES

[1] *Vukobratović M., Juričić D., Contribution to the Synthesis of Biped Gait*, Proc. of IFAC Symp. on Technical and Biological Problem on Control, (Erevan, USSR, 1968)

[2] *Juričić D., Vukobratović M., Mathematical Modeling of Biped Walking Systems*, ASME Publ. 72-WA/BHF-13 (1972)

[3] *Vukobratović M., Borovac B., Zero-Moment Point- Thirty Five Years of its Life*, Int. Jour. of Humanoid Robotics, Vol. 1, No.1, (2004), pp. 157-173

[4] *Vukobratović M., Borovac B., Raković M., Potkonjak V., Milinović M., On some aspects of humanoid robots gait synthesis and control at small disturbances*, Int. Jour. of Humanoid Robotics, Vol. 5. No. 1., (March 2008), pp 119-156