Computer Vision System as Part of Bio-mechatronic Rehabilitation Simulator

Sergey M. Sokolov, Alexander K. Platonov, Andrey A. Boguslavskiy, and Oleg V. Triphonov

Keldysh Institute for Applied Mathematics RAS, Moscow, Russia
sokolsm@list.ru, platonov@keldysh.ru, anbg@mail.ru, tob@imail.ru

Abstract. There is a description of the first stage of researches aimed at equipping with the vision system ("VS") for the rehabilitation simulator being developed for the rehabilitation of spinal patients who suffer paraplegia. Based on the VS information it is supposed to develop some software tools to solve the issue of mechatronics of the bio-training simulator in order to create artificial motions of the paralyzed legs imitating natural legged movement. There's discussed a hardware- and software of the system, methods of data-acquisition concerning the leg movements of a healthy person. There're given results of the first experiments aimed at acquiring data needed for the analysis of the geometrical parameters of the leg movement. There've been received some accuracy assessments to define angles and angular velocities in the hip, knee joint, and ankle joint.

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Keywords: bio-mechatronic rehabilitation simulator, vision system, geometrical parameters of walking, artificial leg movement.

1 Introduction

One of the main problems of medicine is the rehabilitation of spinal patients with paraplegia, i.e. legs motionlessness caused by a backbone trauma. At the rehabilitation simulator when studying the spinal cat in the Physiology Institute n.a. I.P. Pavlov (hereinafter "IPh") there've come a famous experimental result, i.e. after making some special effects the spinal cat began to walk almost independently. This result opened some hope for the possibility to cure people of a similar serious illness. As a note, the effect of stepping generators recovery in the medulla spinalis of the spinal cat was obtained by IPh expert Mr. O.A. Nikitin, Biological Sciences PhD, who not only applied the regular cat's walking at the simulator, but, which is also important, made long-time massaging of the cat's hind feet on his knees while making forced movement of the cat's feet to the beat of walking [1].

With these experiments IPh showed that the key thing of the possible Paraplegics rehabilitation is a poorly-studied problem of organizing afferent (centripetal) signals coming to the cerebrospinal axis during the rehabilitation walking on the simulator.

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These afferent signals are formed with the nerve endings of a foot and musculoskeletal system of an animal and a human being at the moment of positioning legs, and the following supporting and shifting of legs. Meantime, the formation of these afferent signals with the simulator is needed not only to rehabilitate the stepping generators in the medulla spinalis, but, which is also important, to prevent any atrophy of inactive muscles and dying of the nerve cells related to the muscles during the *apoptosis*, i.e. termination of physiological processes in the muscles and nerve endings in case of their inactivity.

Researches concerning the formation of afferent and stimulating signals were arranged by IPh n.a. I.P.Pavlov together with Physical Training Academy (Velikie Luki town) and Institute of Medical-and-Biological Problems at the Russian Science Academy (hereinafter "IMBP") . The works were also done in the USA with the participation of the Russian scientists. These researches have acute need for the development of mechatronic means of managing and synchronizing the movement processes with the processes of forming some stimulating effects on the nerves of the back bone and return afferent signals within the multilevel nerve system for the motion synthesis of a human being.

In terms of applying these results in mid-nineties there appeared an acute issue concerning the creation of a specific bio-mechatronic simulator for a human being which would differ from a usual treadmill-type apparatus and would be equipped as a medical rehabilitation simulator with effector and sensor control elements. This simulator is needed to study the processes of docking the management of high-power engines of legs drive components with the low return signals concerning their physiological condition.

The important place in the system of "sensing"/information supply for the mechatronic simulator is given to the Vision System (VS). VS permits to non-connately register movements of both the parts of the patient's body and parts of the simulator. VS solves the important issue of verifying the movement models of the simulator, and mainly the control of correspondence of the patient's feet movements in the simulator with the natural movements when walking.

One of known systems for registration of parts of a body movements is the system using magnetic markers. There is a positive experience of use of electromagnetic systems of type Spatial Tracking System (Fastrack™ Polhemus), Flock of Birds, MiniBirds and TrakStar (Ascension Technology Corporation). Such system is successfully applied to control of hands movements [2-4]. Application of similar system has a number of the restrictions which are not allowing effectively of it to use as a part of the projected rehabilitation simulator. To restrictions are: a working zone (a range of controllable movements) less than 1 m; necessity of removal from a working zone of all metal subjects which essentially influence accuracy of work. Overcoming the specified restrictions of system on the basis of magnetic markers, the vision system should provide accuracy of movements registration not worse, than ±3~5 mm (average parameter of electromagnetic system).

On the first stage of the project execution there has been selected the following way for the development/formation of VS as part of the simulator. The software is based on the frame for the stereo-system design (fig.1-2) and tracking algorithms for the small targets [5, 6]. The hardware is formed under COTS technology with account of the world and own experience in VS development.

2 Packaging of the VS Hardware

VS tracking of the human movements has been used for a long time [7]. Most of works are known for the research of the efficiency of the sportsmen's movements and for the creation of various effects in the cinema. With the recent growth of the capacities of computer technologies and hardware support for the collection and primary processing of the visual data, there have been created compact devices for a wide range of users. These devices allow in ordinary conditions to rehabilitate the general kinematics of the observed person's action [8]. Almost in all enlisted systems the kinematic model of a human leg is rather sluggish, mainly in the tibio-tarsic. Here, as a rule, there's defined one point [8] or two pints. At the same time, anatomic features of the leg constitution and their detailed observation say that the actual legs movement is definitely more complicated and demands a more appropriate model when rendering. Moreover, the accuracy of feet movements' determination shall be very high with regard to the range of observed movements. With the foot size about 1000mm and space movements within one step cycle (two steps) of about 1600mm, it is necessary to fix shifting of the concerned objects with millimeter accuracy. VS characters demand a range of the described area with one vision field (VS more accurately register shifting of the objects within one vision field, which do not need "linking" of various vision fields). Thus, qualitative estimations of the VS characteristics are being formed in order to be applied as a part of the bio-mechatronic simulator.
The basic thing is the high-resolution cameras with the following characteristics, i.e.:

- resolution 1600x1200, color model RGB, 8 bit/color channel;
- external synchronization (allows to arrange a stereo pair to watch dynamic objects);
- digital output Gigabit Ethernet;
- progressive scanning (access to the random fragments of raster);
- frequency of visual data input from 15 to 200 hz.

These resolution characteristics allow to receive the accuracy of the space resolution when registering:

- person's movements when walking up to 3mm;
- movements of the patient's feet and those of mechanical parts in the rehabilitation simulator up to 1mm.

Light-emitting diodes (fig. 3, 4) are applied to mark the interesting parts of the patient's body. This non-expensive thing definitely accelerates and increases the effectiveness of the development, mainly on the stage of forming an experimental model of the rehabilitation simulator.

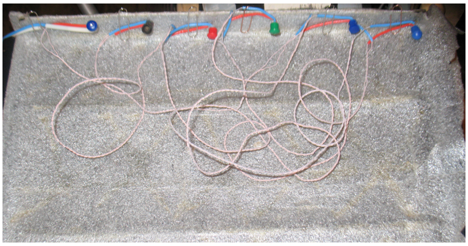


Fig. 1. Light-emitting diodes (without fixing devices)

In order to provide verification of, first, kinematic, then dynamical schemes/ models of the observed objects, it is necessary to separate from the visual data some invariant peculiarities, i.e. characteristic points, to be reference points for the establishment of mathematic models for the movement of concerned objects. In previously uncertain conditions of the breadboard model of the rehabilitation simulator, when it's hard to unambiguously determine objects in the video-camera vision field while the system adjustment for the recognition of a new object demands significant efforts and time, the location of the known objects in the video-system vision field substantively simplifies the task of determining the concerned objects.
Requirements for the markers:

- to provide fixture on the human body with ±1 mm accuracy;
- to provide repeatability for the attaching point
- to clearly indicate (observation on all movement stages, simplicity in terms of separation on brightness and geometry) the concerned place of the human body or details of the rehabilitation simulator
- Fixing convenience (not to impede moving, other equipment)

The structure of the applied marker is shown on fig. 2. The marker is done of two parts, i.e.: cone-shaped part - the base with the incorporated piston which provides the attachment to the human skin or to the smooth surface of the dummy, and a cylindrical element with a fixed light-emitting diode and battery.

To collect and process the visual data a common laptop with the following characteristics is used: CPU Intel Core i5 3.4 GHz, RAM 4 Gb.

Fig. 2. Structure of the luminous marker (left: overall view, right: attachment to the human leg)

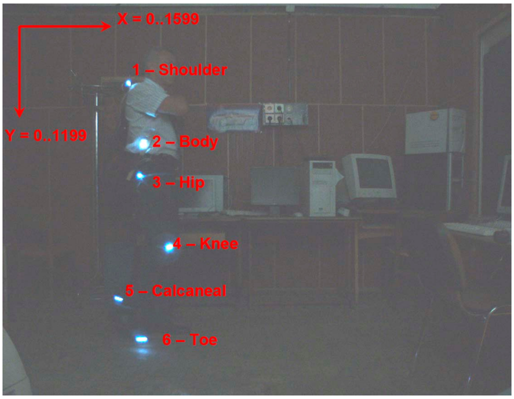


Fig. 3. Location of markers on the human being on the side. Four markers with numbers 3 – 6 are fixed on the leg.

3 Collection and Processing of the Visual Data

The task of detecting the moving marker icons on the images may be referred to the tasks of tracking small targets. The shape of a small target may change with the time due to the change of orientation of object with regard to the visual detector, and, as a result, of discretization errors at the interface of the icon when making a digital image. As a whole, the shape is not a reliable character of a small object. This definite restriction complicates the application of a target model on the image in the tracking system.

Circular markers on the images are applied quite frequently [9, 10, 11]. In the work [12] ref. the analysis for the accuracy of positioning the location of markers when comparing the markers presented as circular icons and chess squares it's noted that the angles of chess squares are less liable for moving during projective transformations and nonlinear distortion deformations compared with the circular markers. This effect becomes important when we have distortion deformations of the camera lens [9]. The markers' layout of supporting points of the human foot or dummy as chess squares is difficult for execution and inconvenient in practice. Thus, as already noted, for the above-described researches we used markers, which form of icons is similar to the circular form on the image (fig. 2, 3). In [5, 6] we review the structure of algorithms for the detection and tracking of a small-size target on the sequence of images.

Similar to the approach described in [5, 6], the algorithm of markers' tracking on the sequence of images is divided into two parts, i.e. initial detection of images and tracking these icons.

Algorithm of initial detection is based on the processing of the image within a square sliding window, which dimensions are several times bigger than the dimensions of the marker (4-5 times bigger). In every position of the window there's performed a thresholding with the separation of an image of the brightest connected component. Coordinates of the center of gravity of the components, which dimensions and form are consistent with the marker icon, are noted as candidates for the tracking.

After the initial processing of the image, on the following images of the sequence there's provided some tracking of the icons of the images. In the position of the predicted location of every marker there's preformed a thresholding which is analogous to the initial detection algorithm. For the account of the time reduction by excluding the image processing with the sliding window, the time needed for the markers detection is decreased by 10-15 times [5, 6].

4 Experiments with the Pilot System

The task of the experiments on this stage of researches was to determine the system capacities in terms of velocity and accuracy of recording the movements of the concerned objects. As such objects we used some marked parts of the human legs and parts of the dummy simulating the positioning of the patient's feet in the rehabilitation simulator.

The following kinematic scheme of the human foot (on the first stage it's flat) (fig. 4) is proposed. In the performed researches the experiments were arranged within traditional models (within 3-6 markers).

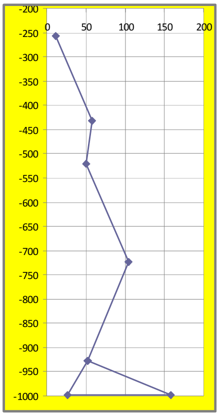


Fig. 4. Example of a flat pivoted model of a human foot which takes into account the peculiarities of the ankle-joint anatomy

Based on the VS measurements there're calculated values of the angles and angle velocities in the pivoted foot model (fig. 4). These data are calculated for the markers located in the places corresponding to the model of the human feet joints, i.e.: hip, knee-joint, ankle-joint (3, 4, 5, 7 on fig. 3 and 4).

The experiment controlled the movements of a person walking 5km/h (~ 1,4 m/s). There were tracked movements within four steps, i.e. two cycles of walking in the straight and opposite directions.

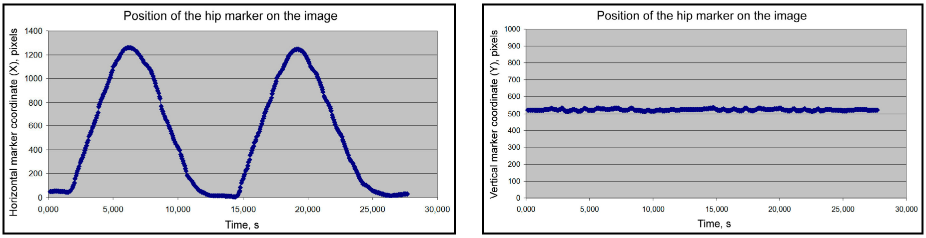
Movements of the dummy's legs in the rehabilitation simulator (fig. 5) were done "manually" one-by-one with each degree of movement. The velocity of movements approximately (measured with the second-counter) corresponded to the velocities of legs walking 5km/h.

a) b)

Fig. 5. Dummy with the markers as part of a model of the bio-mechatronic simulator. a) markers fixed on the dummy; b) the dummy as part of a model of the bio-mechatronic simulator.

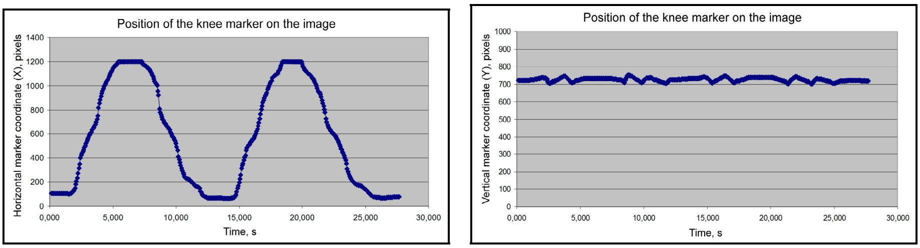
4.1 Determination of Kinematic Characteristics of a Human Walking

Fig. 6-9 show examples of determining the location of markers on the human leg. σ_x, σ_y – mean square deviations of the measured quantities along the axis Ox and Oy respectively. These characteristics of the measurement accuracy are obtained as a result of comparing the measured coordinates of the markers on the picture with the results of the smoothing averaging filtration with the time window 1.5 mm/pixel. The scaling coefficient is about 1.5 mm/pixel.



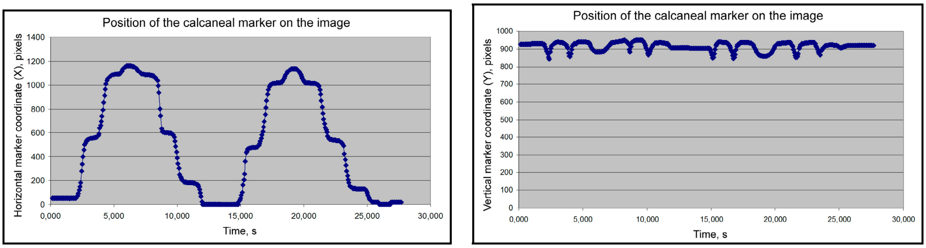
(a) (b)

Fig. 6. Results of determining the location of the hip marker on the image (σ_x≈3.1 pixel, σ_y≈0.8 pixel). (a) Horizontal marker coordinate on the image; (b) vertical marker coordinate on the image.



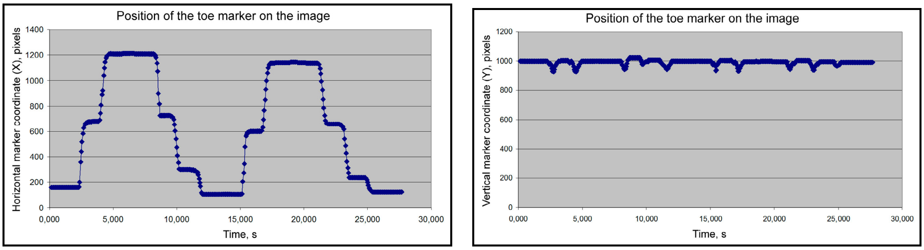
(a) (b)

Fig. 7. Results of determining the location of the knee marker on the image. (σ_x≈4.4 pixel, σ_y≈1.2 pixel). (a) Horizontal marker coordinate on the image; (b) vertical marker coordinate on the image.



(a) (b)

Fig. 8. Results of determining the location of the calcaneal marker on the image. (σ_x≈6.6 pixel, σ_y≈3.7 pixel). (a) Horizontal marker coordinate on the image; (b) vertical marker coordinate on the image.



(a) (b)

Fig. 9. Results of determining the location of the toe marker on the image. (σ_x≈9.4 pixel, σ_y≈3.8 pixel). (a) Horizontal marker coordinate on the image; (b) vertical marker coordinate on the image.

On the example of chain “hip – knee” the accuracy of determination is σ≈14 mm and may be increased at the account of changing the method of markers attachment (see p.2).

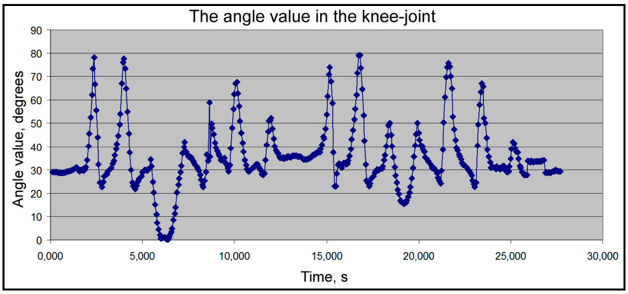


Fig. 10. The value of angle in the knee-joint under the results of processing the location of markers in the human walking process

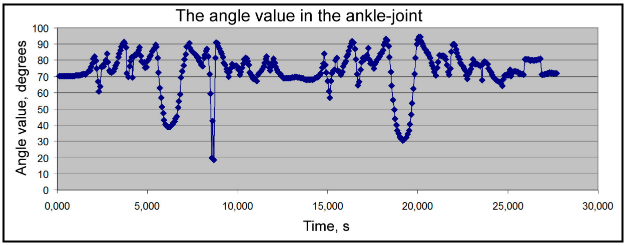
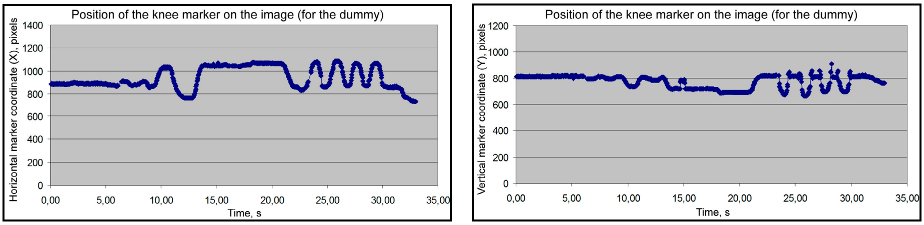


Fig. 11. The value of angle in the ankle-joint under the results of processing the location of markers in the human walking process

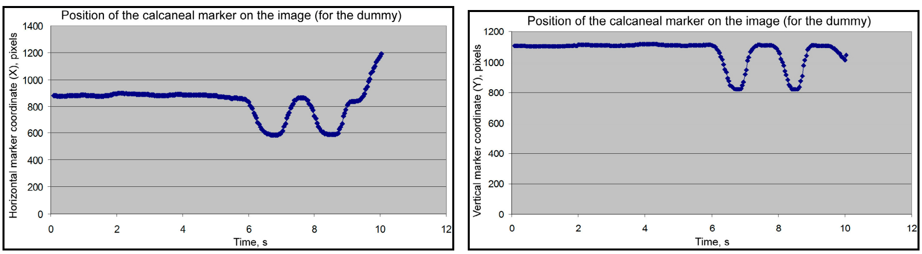
4.2 Determination of Kinematic Characteristics of the Dummy's Movements

Fig. 12-13 show examples of determining the location of markers on the dummy's leg. σ_x, σ_y mean square deviations of the measured quantities along the axis Ox and Oy respectively. These characteristics of measurements accuracy are obtained as a result of comparing the measured coordinates of the markers on the image, with the results of the smoothing averaging filtration with the time window 0.2 s. The scaling coefficient is about 1.5 mm/pixel.



(a) (b)

Fig. 12. Results of recording the location of the knee marker on the image. ($\sigma_x \approx 3.6$ pixel, $\sigma_y \approx 6.2$ pixel). (a) Horizontal marker coordinate on the image; (b) vertical marker coordinate on the image.



(a) (b)

Fig. 13. Results of recording the location of the calcaneal marker on the image. ($\sigma_x \approx 3.2$ pixel, $\sigma_y \approx 3.6$ pixel). (a) Horizontal marker coordinate on the image; (b) vertical marker coordinate on the image.

5 Conclusion

The work describes the VS packaging and researches to be included into the biomechatronic rehabilitation simulator, done under COTS technology. The performed researches show that the reviewed VS permit to record the movements of the human legs with high accuracy within a flat model, both in the natural walking and in walking simulation as provided by the simulator. Meantime, there's provided convenience of the non-contact registration and cost-effectiveness (for the account of unification of various VS components).

The obtained accuracies permit to apply VS as a part of control system for the simulator when doing natural human legs' movements.

The future of the just-described studies will be the development of a system for recording space movements of the concerned objects (transfer to 3D model). On the following stages, when recording the location of the whole equipment and conditions for the surveillance over the rehabilitation simulator space, it's possible to replace the specific markers with different clothes elements or parts of equipment.

References

1. Okhotsimsky, D., Nikitin, O., Gerasimenko, Y., Serbenjuk, N., Mitutsova, L., Delchev, K., Vitkov, V., Platonov, A., Yaroshevsky, V.: A biomechanical stimulator for scientific-experimental study of the regeneration of spinal cord locomotion capabilities after traumatic break. In: Proc. of the Int. Conf. Advanced Problems in Mechanics 2005, Minisymposium on Biomechanics, St. Petersburg, Russia, pp. 394–400 (2006)
2. Biryukova, E.V., Roby-Brami, A., Frolov, A.A., Mokhtari, M.: Kinematics of human arm reconstructed from Spatial Tracking System recordings. Journal of Biomechanics 33(8), 985–995 (2000)
3. Prokopenko, R.A., Frolov, A.A., Biryukova, E.V., Roby-Brami, A.: Assessment of the accuracy of a human arm model with seven degrees of freedom. Journal of Biomechanics 34, 177–185 (2001)
4. Platonov, A.K., Frolov, A.A., Birjukova, E.V., Prjanichnikov, V.E., Yemelyanov, S.N.: Biomechanics methods in the training apparatus of a human hand. Preprint KIAM RAS, No 82 (2012)
5. Boguslavsky, A.A., Sokolov, S.M.: Algorithms for tracking a small-sized target as part of VS. In: Materials of the Scientific School-Conference on Mobile Robots and Mechatronic Systems, pp.81-90. MSU n.a. M.V. Lomonosov, Moscow, Russia (2004)
6. Boguslavsky, A.A., Sokolov, S.M.: The realtime Vision System for small-sized target tracking. Int. J. Computing Science and Mathematics 1(1), 115–127 (2007)
7. Rosenhahn, B., Klette, R., Metaxas, D. (eds.): Human Motion. Understanding, Modelling, Capture and Animation. Springer (2008)
8. Kinect for Windows, Microsoft Corp., `http://www.microsoft.com/en-us/kinectforwindows/`
9. Luhmann, T., et al.: Close Range Photogrammetry: Principles, Techniques and Applications. Wiley (2007)
10. Heikkilä, J., Silvén, O.: A four-step camera calibration procedure with implicit image correction. In: Proc. IEEE Conf. on Computer Vision and Pattern Recognition (CVPR 1997), pp. 1106–1112 (1997)
11. Wohler, C.: 3D Computer Vision. Springer (2009)
12. Mallon, J., Whelan, P.F.: Which pattern? Biasing aspects of planar calibration patterns and detection methods. Pattern Recognition Letters 28(8), 921–930 (2006)