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Satellite Mock-Up Position and Orientation Determination System Based on Block of Inertial Sensors and Star Tracker

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Mock-Up Position and Orientation Determination System Based on Block of Inertial Sensors and Star Tracker. D. Bindel, D.S. Ivanov, D.O. Nuzhdin, M.Yu.Ovchinnikov, S.P. Trofimov,. Preprint of KIAM RAS, Moscow, 30 Pages, 24 Figures, 7 References.

Attitude and position determination algorithms based on IMU block (accelerometers and gyro sensor) and star tracker measurement are developed and investigated. Algorithms are realized on laboratory mock-up, experimental results are analyzed.

Key words: attitude determination algorithm, accelerometer, angular velocity sensor, star tracker

Система определения положения и ориентации макета спутника на основе блока инерциальных датчиков и звездного датчика. Д. Биндель, Д.С.Иванов, Д.О. Нуждин, М.Ю. Овчинников, С.П. Трофимов. Препринт ИПМ им.М.В.Келдыша РАН, Москва, 30 страниц, 24 рисунка, библиография 7 наименований.

Построены и исследованы алгоритмы определения вектора состояния тела с использованием двух независимых средств определения его ориентации и положения на горизонтальном лабораторном столе – звездная камера и блок инерциальных датчиков (двухосный акселерометр и датчик угловой скорости). Алгоритмы реализованы на макете спутника, приведены и проанализированы результаты экспериментов.

Ключевые слова: алгоритм определения ориентации, акселерометр, датчик угловой скорости, звёздный датчик

1. Introduction

The laboratory facility called LuVeX (**Lu**ftkissen **V**ehikel **Ex**periment) (Fig.1) is developed at ZARM, the Center of Space Technology and Microgravity of the Bremen University. It allows us to explore the satellite dynamics, to give a work-out to different types of satellite formation cooperation and to verify the satellite group motion control algorithms [1, 2]. At the moment there are two mock-ups which enable to move on an air-cushion and set in motion by compressed-air thruster engines. Elaborating the engine control algorithms provides the experiments with control of the mock-up’s position and orientation.

Fig. 1. ZARM mock-ups

In this paper an algorithm based on star camera and inertia measurement unit (IMU) are considered. The IMU block consists of single axis angular velocity censor and two axis accelerometer. The star camera represented by web-camera recognizing a «stars» - small lamps above the table at the ceiling. First, in this paper an explanation of attitude and position determination algorithms based only on star camera and only on IMU are presented, advantages and shortcomings of each algorithm are considered. Then, an algorithms used both of two measurement instruments is developed. Moreover, it is shown that this algorithm has no shortcomings of algorithms based on only one measurement tool. In this paper also laboratory test results are presented and analyzed.

2. A stars recognition algorithm

A standard cycle of stars recognition are shown at Fig.2.

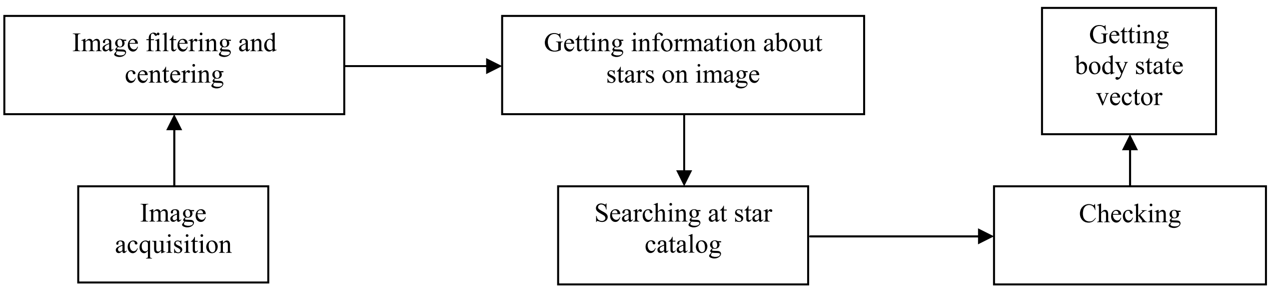

Fig.2. A standard cycle of star recognition

There are following restriction on star identification method at ZARM stand:

1. impossibility of interstar angular distances measuring because of its dependence of distance between webcam and ceiling;

2. no difference in star brightness;

3. a simple webcam using as star camera, that subjected by different distortion;

4. Insufficient predictability of «orbital» mock-up motion, that makes impossible to use recursive algorithms.

As consequence of previous restriction are chose a calibrating invariant algorithm «lost-in-space» based on Delaney triangulation (DT).

A Delaunay triangulation for a set of points in the plane is a triangulation such that no point in that set is inside the circumcircle of any triangle in DT (Fig.3). Delaunay triangulations maximize the minimum angle of all the angles of the triangles in the triangulation; they tend to avoid skinny triangles. Also for defined set of points DT is unique.

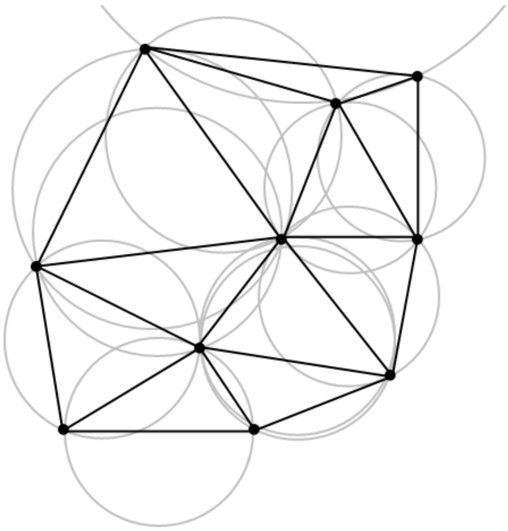

Fig.3. An example of Delaney triangulation

For all stars at ceiling one can form a unique DT and make a catalog of all Delaunay triangles, that consist of position information of each star of each triangle and minimal and maximal triangle angles. Next, in case that in field of camera view there are sufficient number of stars then the most of image DT triangles will be in catalog of DT of whole ceiling (Fig.4). Then, one can search image DT triangles at catalog with defined accuracy. After that for each recognized triangle one can calculate a position of center of image. In case of position coincidence for some set of triangles we'll get a true current value of position. This was short explanation of used star recognition algorithm.

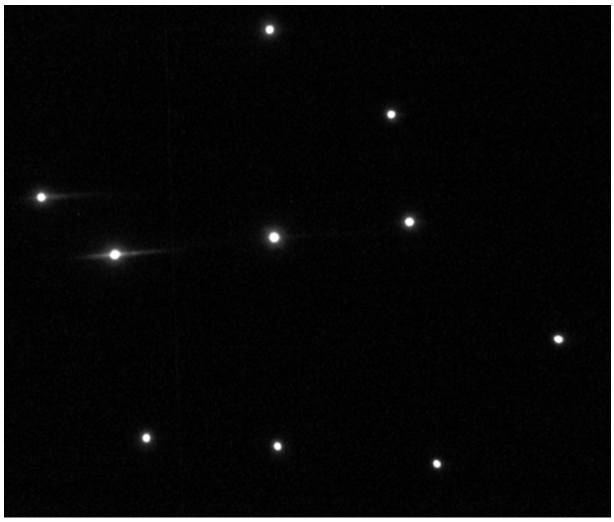

Fig. 4. An Example of image of ceiling

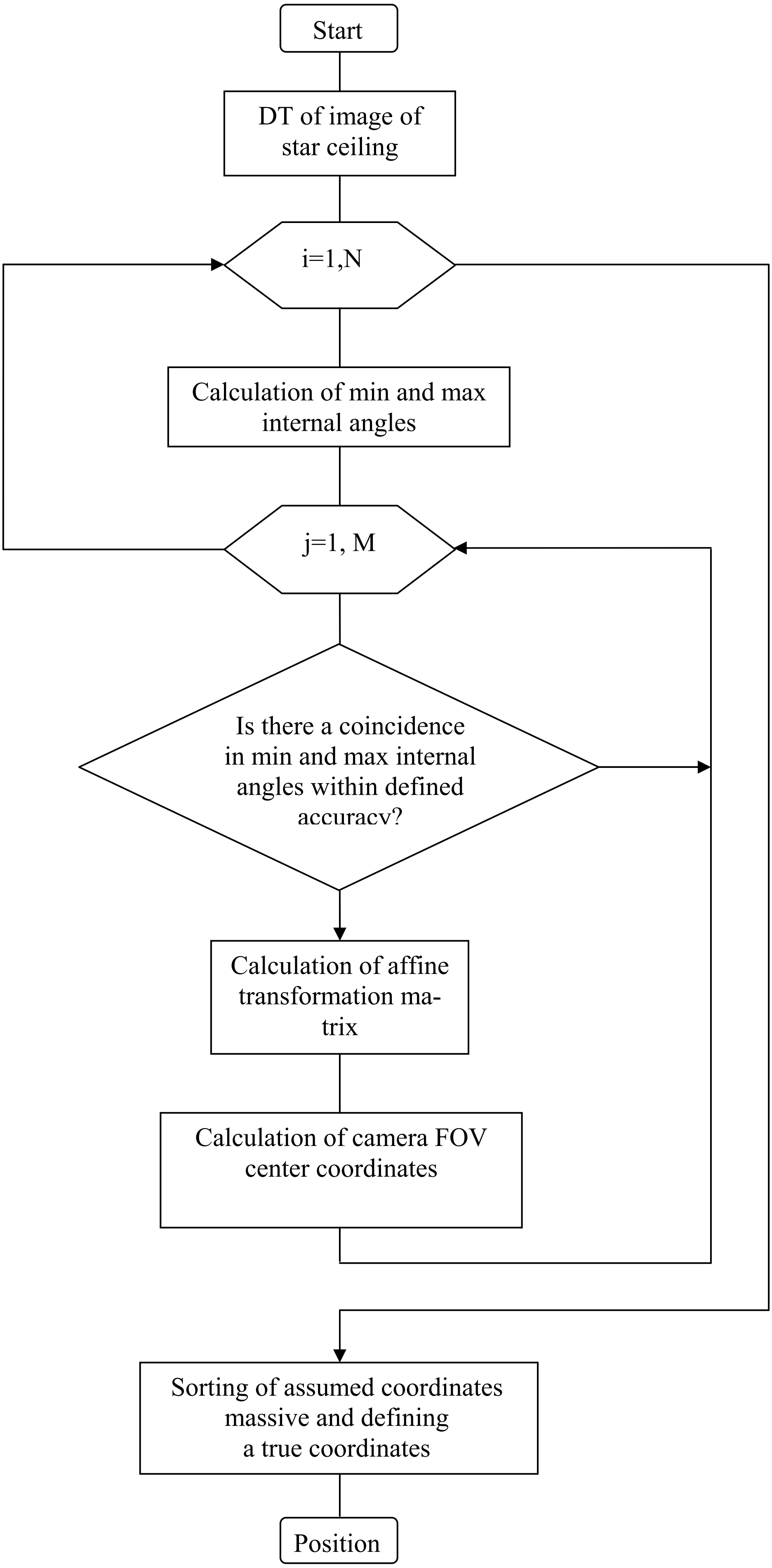

Fig.5. Scheme of algorithm

Main stages of algorithms are shown at Fig.5. «Start» means the moment when all stars pixel coordinates of image are known. Here N – is the number of DT triangles of image, M – is number of triangles of catalog. Star ceiling has 180 stars. Catalog of DT triangles has 322 triangles.

2.1. Algorithm realization

The considering algorithms was realized in Matlab. An additional computer (lop-top) was installed on the top of the LuVeX for solving position and orientation determination task by webcam use (Fig.6). The calculated information was sent from lop-top to on-board computer via Wi-Fi .

Let us consider characteristics of realized algorithm.

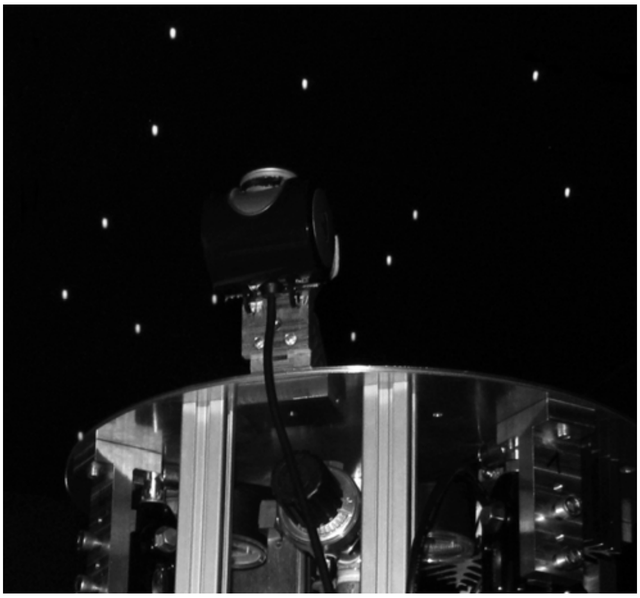

Fig. 6. Webcam

Speed of acquisition of state vector

Speed of acquisition of state vector means a time between image acquisition and getting a position. At Fig.7 results of one of experiment are shown. During this experiment the mock-up moved manually along the table perimeter. A linear center mass mock-up velocity are shown by gray pointer and a places where the algorithm couldn't calculate a position are marked by black stars. At Fig.8 dependence of time between two successful recognition on time during this experiment are presented. As one can see the mean time spent to calculate the position is near 0.6 s. But sometimes the algorithm fails because of nonsufficient stars in camera FOV for making DT or because too big linear velocity that makes image of star careless (centers of stars calculated with too big mistakes).

Accuracy

Let estimate an accuracy of such a method of position determination. First, let leave the mock-up at rest for a while and let see the difference in output values. At Fig. 9 the example of such experiment is shown. So, the achieved accuracy is near 1mm in position and 0.1 degree in orientation. But these values are the best because in case of mock-up moving the star images became blurry and the accuracy became worse.

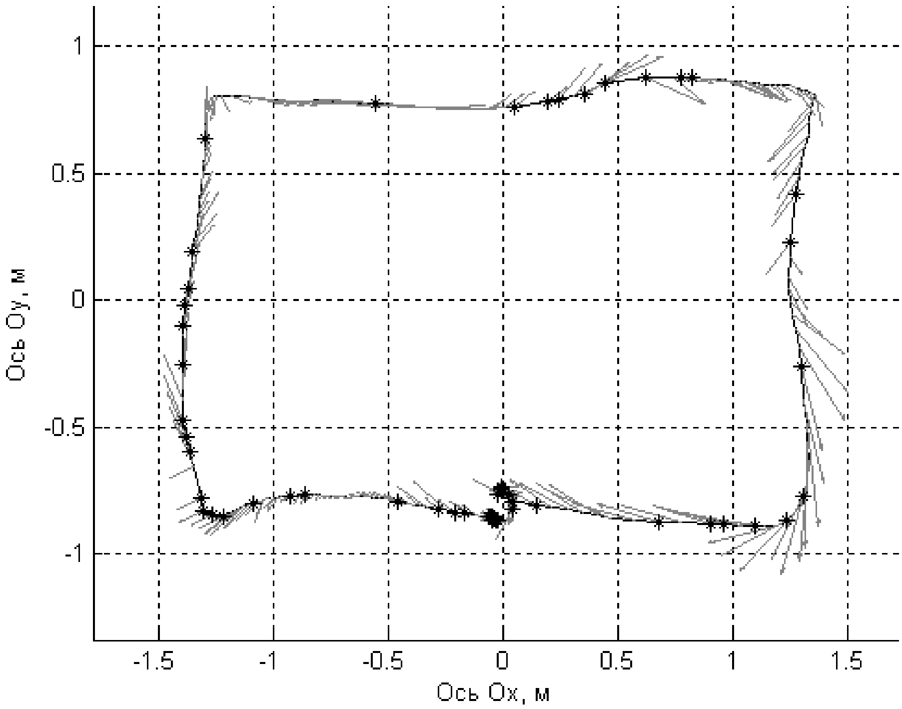

Fig. 7. An example of some experiment results
A linear center mass mock-up velocity are shown by gray pointer.
Places where the algorithm couldn’t calculate a position are marked by black stars.

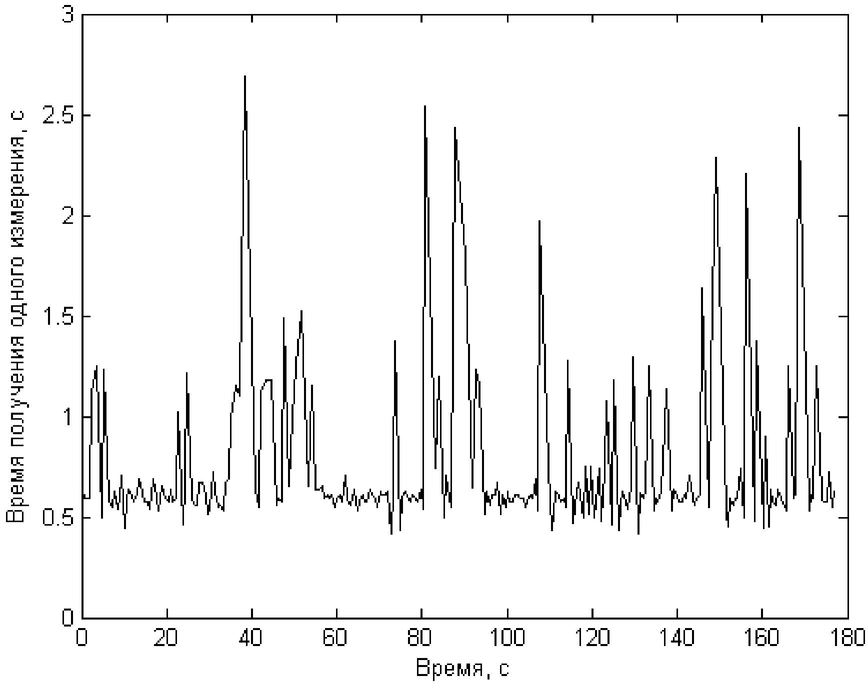

Fig. 8. Dependence of time between two successful recognition on time during this experiment

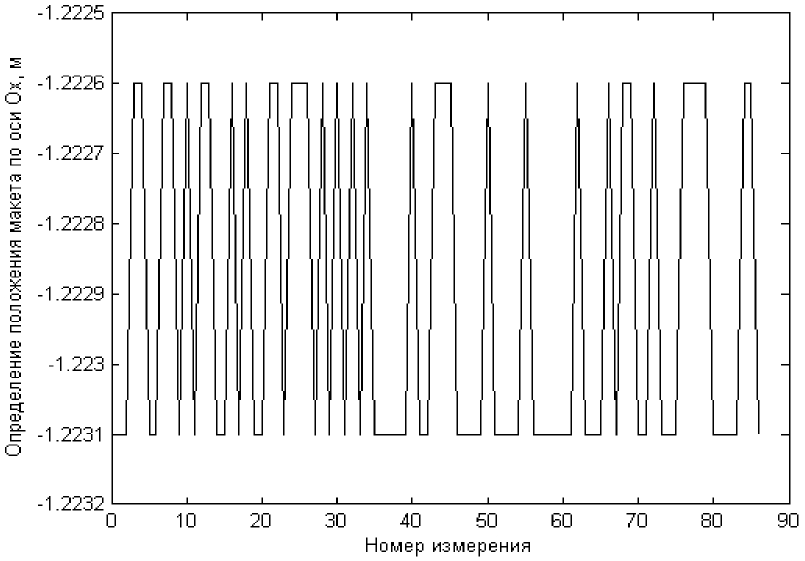

Fig.9. Accuracy of position determination at mock-up rest

3. An attitude and position determination algorithm based on IMU measurements

3.1. A state vector determination algorithm

A state vector algorithm consists of two following parts.

3.1.1. Preliminary calibration

Sensors calibration is necessary for sensors bias and also for IMU mounting on mock-up inaccuracy determination. This calibration should be done before the every experiment because the bias values are not stable, a little random and they depend on temperature.

The calibration carried out by the next way. Before execution of the main program the IMU measurement are collected. These values are the sensor biases because the mock-up is at rest at this moment. The IMU mounting errors are also included in these values. So, the IMU measurements are averaging during a few seconds and the IMU biases are obtaining by this way.

3.1.2. Measurement integration

Data processing and integration executed by microcontroller and by on-board computer. First, the microcontroller during infinite cicle read the data from angular velosity sensor and from inclinometer, get bites consisting the values proportional to angular velosity and acceleration in two directions. This values converts to degrees per second and meters per square second correspondly. Next, averaging of the data causes decreasing of the measearement noise. Then, before sending this data to on-board computer the check-sum are calculated. It’s necessary to filter the values that partly lost during the data transmission.

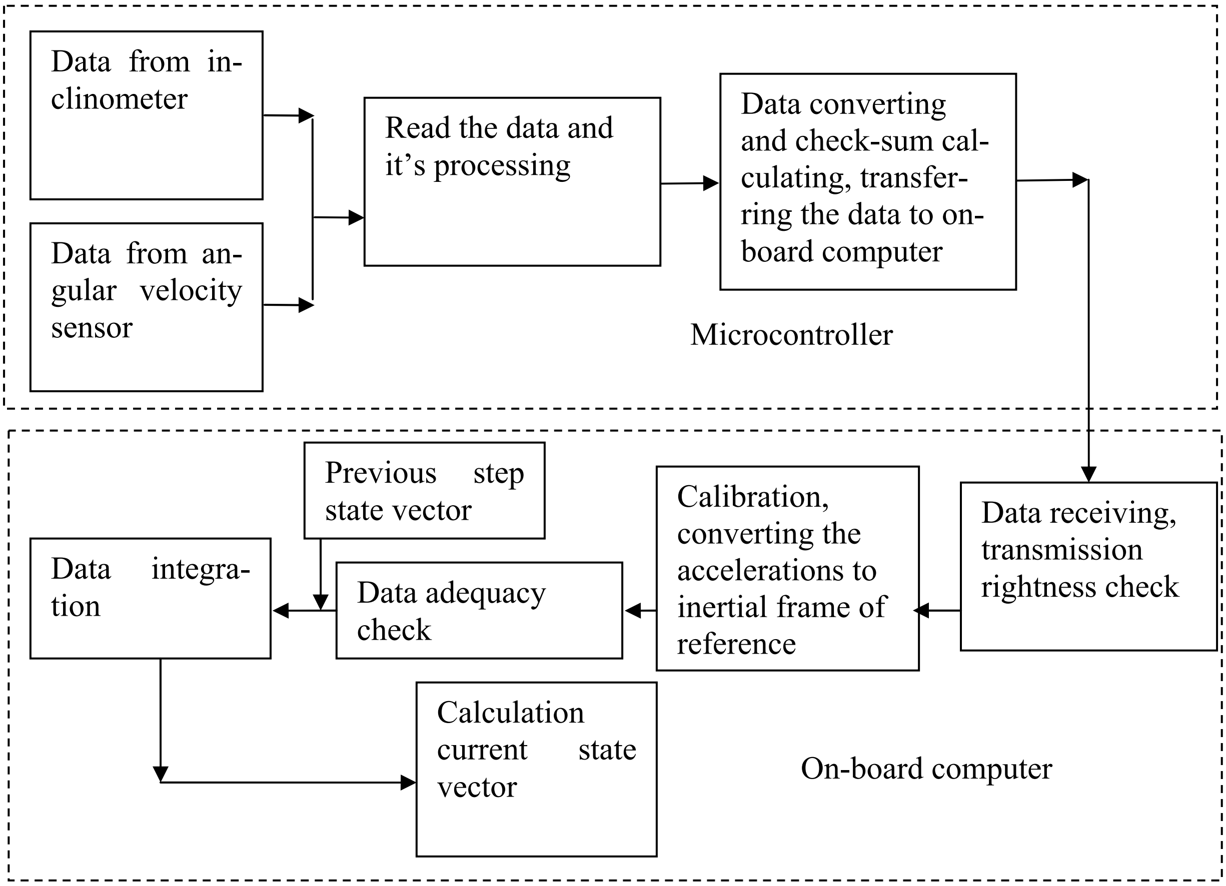

Fig.10. Scheme of the algorithm

After on-board computer data receiving the sensors biases subtract from the measurements. Then, the acceleration converts to the inertial reference frame accordingly next formulas:

$$\begin{cases} a_X = a_x \cos\varphi + a_y \sin\varphi, \\ a_Y = a_y \cos\varphi - a_x \sin\varphi. \end{cases}$$

Here a_X, a_Y - acceleration at inertial ref. frame, a_x, a_y - accelerations at mock-up's ref. frame, φ - rotation angle mock-up's ref. frame to inertial ref. frame, that calculated by angular velocity integration. Next, values a_X, a_Y pass testing if they are anomaly that might be caused by sensors electronics fails. If the values a_X, a_Y are more than 0,5 м/с^2 and angular velocity ω more than 50 град/с they are not considered. After that the integration is executed by following way:

$$\begin{cases} v_X^i = v_X^{i-1} + a_X^i (t_i - t_{i-1}), \\ v_Y^i = v_Y^{i-1} + a_Y^i (t_i - t_{i-1}), \end{cases}$$

$$\begin{cases} X^i = X^{i-1} + v_X^i (t_i - t_{i-1}) + \dfrac{a_X^i}{2} (t_i - t_{i-1})^2, \\ Y^i = Y^{i-1} + v_Y^i (t_i - t_{i-1}) + \dfrac{a_Y^i}{2} (t_i - t_{i-1})^2, \\ \varphi^i = \varphi^i + \omega^i (t_i - t_{i-1}). \end{cases}$$

Here v_X^i, v_Y^i - linear velocity vector components, X^i, Y^i, φ^i - center of mass coordinates at inertial reference frame and rotation angle mock-up's ref. frame to inertial ref. frame, that calculated by angular velocity integration at the moment t_i, t_{i-1}- moment of receiving previous measurements. So, at the each time t_i the next state vector is obtained:

$$\begin{bmatrix} X^i & v_X^i & Y^i & v_Y^i & \varphi^i & \omega^i \end{bmatrix}.$$

3.2. Algorithm realization

3.2.1. IMU description

At figure 11 the IMU-block is shown. It consists of angular velocity sensor, two axis inclinometer and microcontroller.

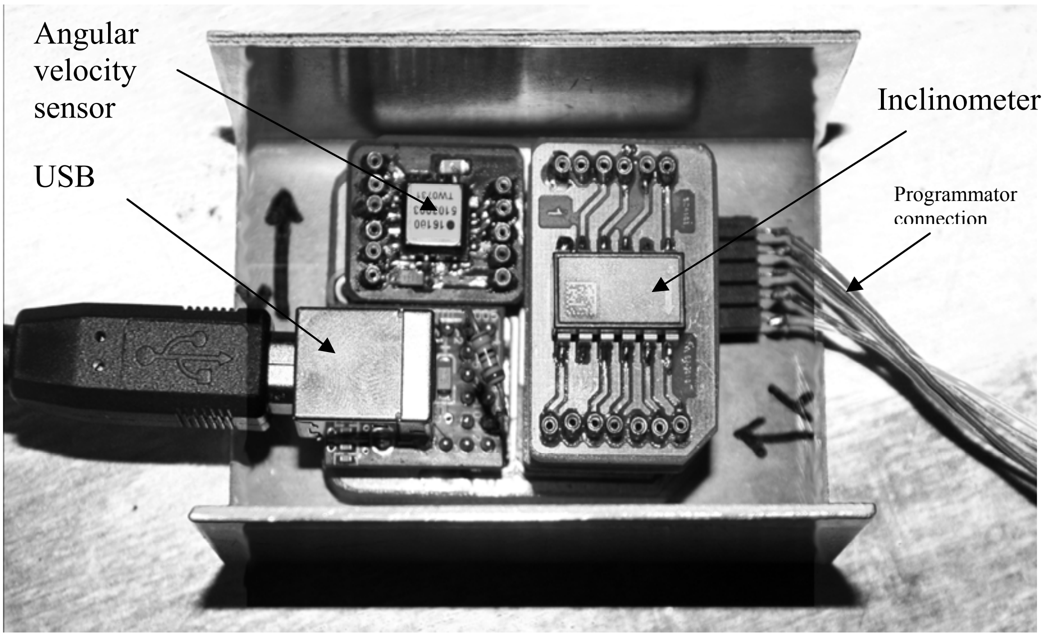

Fig. 11. IMU-block

3.2.2. Experiment results

Consider a few of mock-up state vector determination experiments. First, let consider graphs of acceleration and angular velocity. As shown at fig. 12 the noise of inclinometer is rather significant, but the control values (bold line) are observable. Except the sensor noise there are some measurement peaks probably caused by some periodically flour vibration or unaccounted mock-up internal movements.

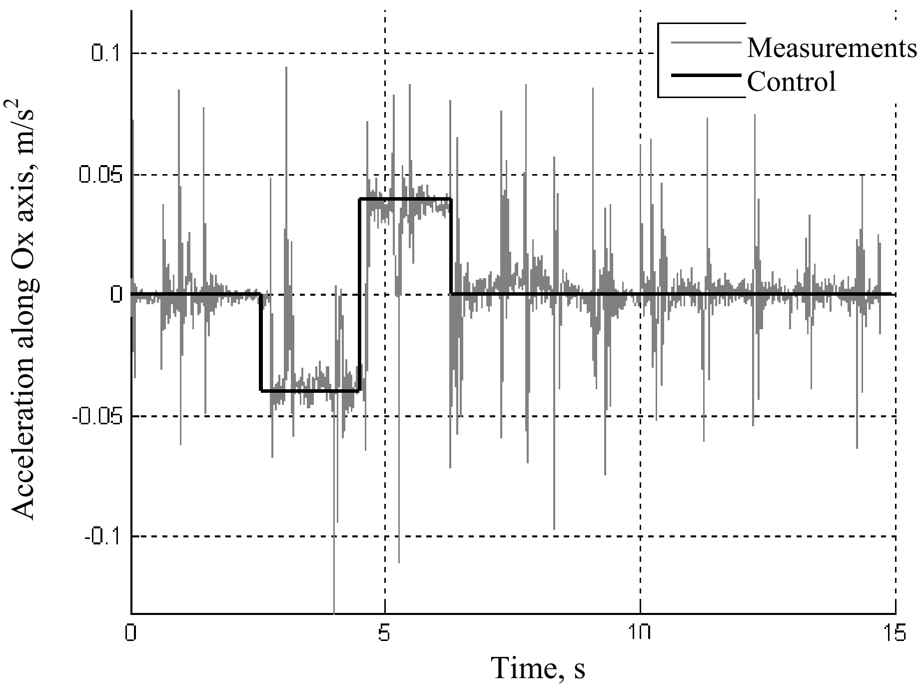

Fig. 12. Acceleration measurements

At fig.13 angular velocity measurements are shown.

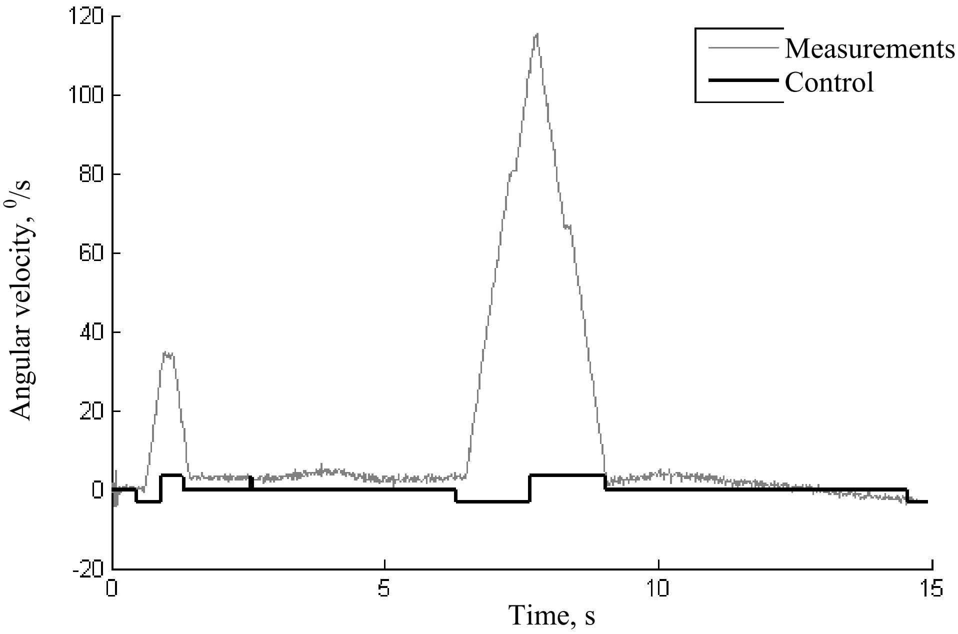

Fig. 13. Angular velocity measurements

Let's consider integration algorithm results and compare it with star-camera measurements. At fig.14 mock-up orientation is shown. One can see that data from star-camera has delay close to 0,6 s.

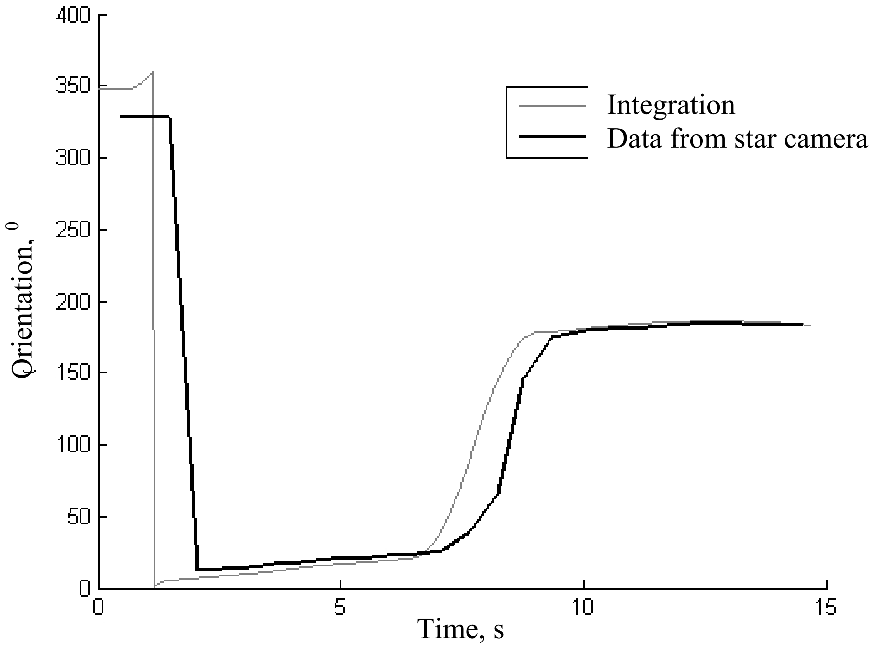

Fig.14 Mock-up orientation

On fig. 15 a mock-up position is shown. One can see that the position calculated by integration diverge from the position with web-cam help quite quickly. This can be explained by the error in calculation of IMU biases. So, the bias error equal to $\pm 0,001 m/s^2$ causes to position error during 10 second equal to $\delta = at^2/2 = \pm 0,05m$, but the accuracy of measurement of acceleration is $\sigma = \pm 0.002 m/s^2$. So, it's rather difficult to determine the bias sufficiently accurate.

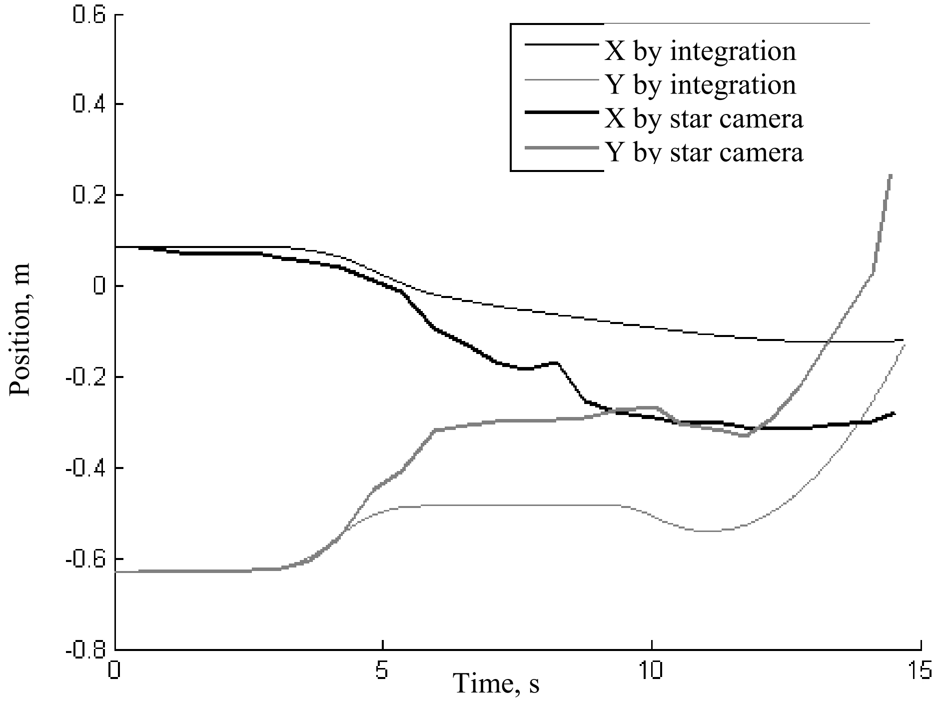

Fig.15. Mock-up position

4. An algorithm based on IMU and star camera measurements

At previous chapters was considered algorithms based on IMU and star camera measurements independently and each algorithm had its own shortcomings and advantages. Here let's consider an algorithm based on both instruments.

4.1. Algorithm description

Consider next algorithm. It starts work when first state vector calculated with star camera help is received by on-board computer. At that moment integration of IMU measurements starts with not so precise initial condition (because the ~0,6 s. delay). At the same time all the IMU measurements are saved. So, when the next web-cam measurement (measurement of state that was 0,6 s. earlier) is coming the second integration (since last web-cam measurement to current moment) with quite accurate initial condition is executed. By this way we have state vector at each moment receiving IMU measurements, there is no delay in calculating state vector and no considerable diverge during two star camera measurements.

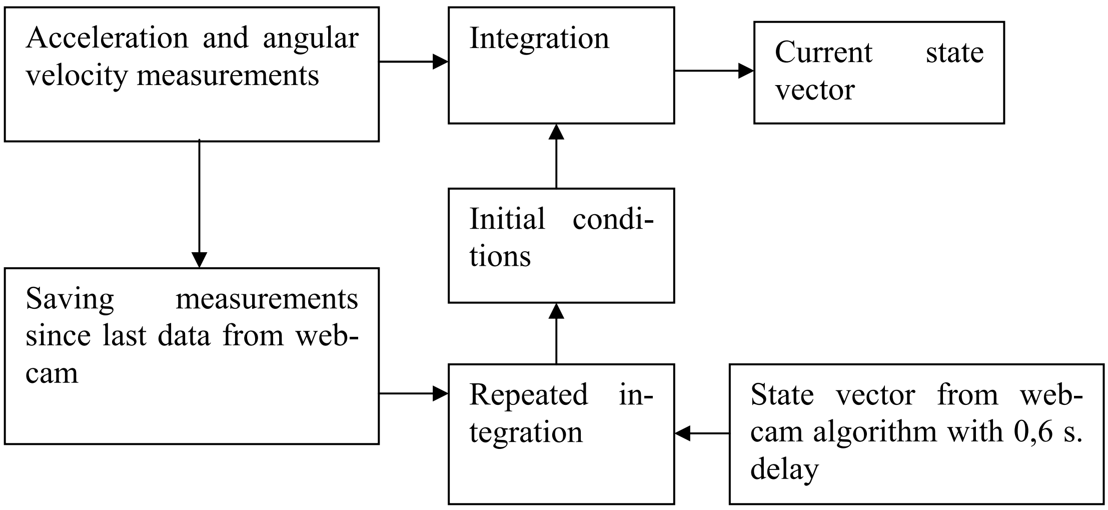

Fig. 16. Algorithm scheme

4.2. Experiments results

On fig.17 and 18 the graphs of position and velocity are shown. Thin lines are the algorithm outputs and the bold ones are data from star camera. So, one can see from figures the accuracy of that algorithms is more than 5 cm.

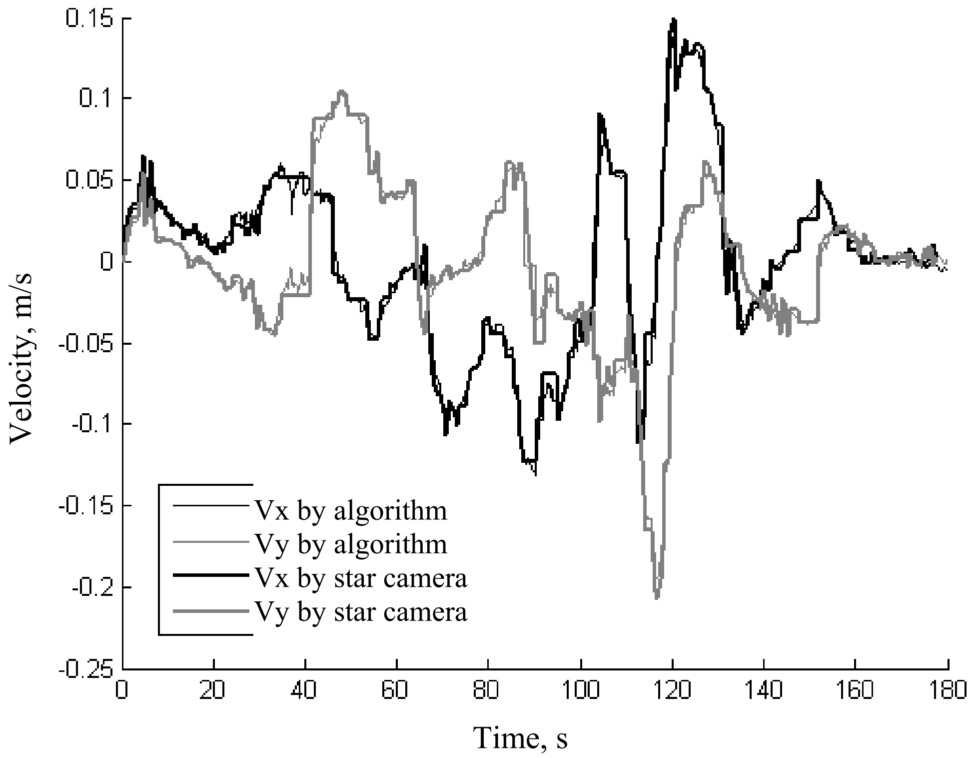

Fig. 17. Linear velocity vector components at inertial ref. frame

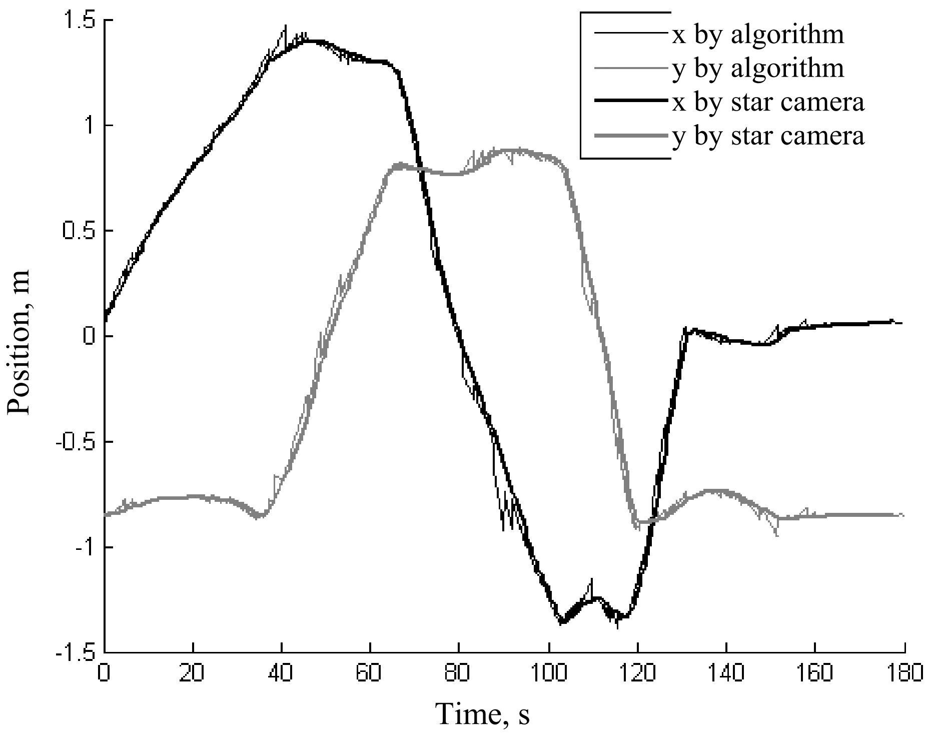

Fig. 18. Mock-up center of mass position

5. Conclusion

At the paper the two independent position and orientation determination instruments (IMU block and star camera) was considered in detail. Algorithms based on both tools was developed and realized on mock-up that can move horizontally along the table surface. And in the developed the algorithm that has several advantages over the previous ones.

Acknowledgments

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