MACIEJ ZASUWA, JANUSZ NARKIEWICZ
Warsaw University of Technology

VISUAL NAVIGATION SYSTEM BASED ON ELEMENTARY IMAGE PROCESSING TECHNIQUES

ABSTRACT

A visual navigation system with a simple pattern matching algorithm was designed and analyzed. A video camera is the system main sensor for image acquisition. It is supported by magnetic compass. A Scene Matching Area Correlation (SMAC) method based on a cross correlation technique is implemented for image processing. The system was tested both in off-line simulations and on-board of a land vehicle. A GPS receiver was used for system calibration and as a source exact position coordinates. The efficiency of the signal processing algorithm during the field tests confirmed efficiency of the methods developed for determination of vehicle position and velocity. A visual navigation system based on simple image processing techniques may be applied on board mobile vehicles in an autonomous way or as a component of integrated navigation system.

Keywords:
image processing, visual navigation, integrated system.

INTRODUCTION

During the last decades the positioning, surveillance and navigation is dominated by satellite navigation methods. Two global satellite systems are in the space so far: American GPS and Russian GLONASS. Within a few years Galileo — European Satellite Navigation System — will be available. The satellite navigation systems are supported by ground and space based augmentation systems like WAAS, EGNOS, LAAS, MSAS, which allow not only higher precision of position, velocity and time determination, but also increase availability and integrity of the signals [6, 15].

The main disadvantage of using GNSS as a sole navigation system, stems from utilization of radio waves for information transfer, which may be purposely jammed or spoofed. This is the main reason for development of integrated navigation systems, composed of several sensors. Dissimilarity of the principles of operation, methods, hardware and software [17] for signal processing are introduced in integrated systems to increase reliability and integrity.

The extensive research effort is undertaken to integrate GPS with Inertial Navigation Systems (INS) and magnetic sensors (compass) [2, 9]. Nowadays it seems to be a standard approach in developing systems for air, maritime and land navigation. Low cost navigation equipment based on other sensors may be an alternative or a support of GPS/INS/magnetic compass.

Visual navigation is the oldest method used everyday by humans for determination of position, in which the relative positions of various objects are determined by an eye perception. In the advent of affordable computers for signal processing and video/photo cameras for image acquisition it is natural to use these devices as sensors in navigation systems. The methods and algorithms developed for video equipment may be also applied in other parts of electromagnetic waves (radio, infrared, microwave etc.) spectrum.

The values of local navigation parameters may be measured using image processing techniques [3, 5, 21] by matching information from sensors with the data stored in the system memory [25]. The methods of visual navigation are similar to algorithms used in terrain — referenced navigation systems applied in aviation, in which radioaltimeters integrated with Inertial Navigation System (INS) or Global Positioning System (GPS) are used.

The advantages of visual navigation are autonomous work and potential high accuracy. The visual system does not broadcast any signals, so it may find various civil and military applications. The disadvantage of visual system is degradation of performance due to poor propagation of light.

It seems that the progress in sensors (video cameras) for image capturing, algorithms and computing technology will allow to develop affordable visual navigation systems.

The main objective of the research presented in this paper was to investigate possibility of application of on-shelf measurement camera and simple image processing algorithms to the visual navigation. The system should be affordable, easy to assembly and should need low computational power.

The first review of applicable image processing algorithms in navigation was done. The selected image processing algorithms were tested both off- and on-line. The system composed of monochromatic camera and supported by GPS receiver and magnetic compass was designed, assembled and tested in the laboratory, and installed on-board of a land vehicle (electric cart). It was calibrated and evaluated during field tests.

The visual navigation system that utilizes simple image processing techniques may be applied on mobile vehicles as a an autonomous system or integrated into other navigation sensors.

APPLICATION OF IMAGE MATCHING TECHNIQUES IN NAVIGATION

In the paper the following nomenclature is applied. A *scene* means the area of the navigation system activity. The scene is recorded as a sequence of images. *An image* is the result of scene recording by the camera in an selected instant of time. The content of image is called a *frame*. A *pattern* means a recognizable part of a frame. Usually it represents selected object in the scene. During image processing the pattern is searched in two or more subsequent frames. The pattern may be pre-recorded before the initialization of navigation system. A *pattern (image) matching* means evaluating a level of correspondence between the data actually acquired and the data stored in the system memory.

Several research results of application of image processing in navigation are reported, mostly aimed on extracting information from noisy signals [27]. The image processing techniques were applied in land, maritime and air navigation. Application of visual methods in land navigation increased safety and comfort by supporting the driver with additional information, which include detection of road environment [23], recognition of lanes and traffic signs, detection of obstacles in urban traffic using stereo vision [12] etc. Contribution of these methods to road safety was proved in [26]. The image processing techniques also find applications in robotics for in-door positioning. The imaging sensors can be both mounted onboard or placed outside the mobile robot.

Both the analytical and artificial intelligence methods are used in visual navigation for signal processing.

The analytical methods have good mathematical background, which is useful in proving convergence, accuracy and code operations, but they are usually very susceptible to the noise of signal. In practice their efficiency may be limited. There are several issues, which should be solved to obtain efficient analytical image matching process, such as possibility of ambiguous solutions (image matching is performed using local information) and the high computational loads. The desired feature of algorithms is internal self testing.

Some analytical image processing algorithms are ill-conditioned, which may lead to computation instability. It may be avoided by adequate assumptions concerning the scene. The condition of finishing the numerical process of (deciding of obtaining adequate level of image correlation) must also be chosen correctly. The algorithms based on logical product of measured and stored data were used in a navigation system of a robot, which follows the mobile object (for example a man) recognizing its characteristic features [10, 26].

The application of methods based on artificial intelligence may shorter the computation time comparing to analytical methods. The most important disadvantage of artificial intelligence methods is their 'black box' nature and sometimes the necessity of elaborative training.

The methods of artificial intelligence (mainly neural networks) were used to develop algorithms for image recognition in [31]. In maritime applications [24] radar and sonar were used as sensors of images, which were matched with the representation of the object on digital map.

The images of vessels were used to recognize the traffic pattern and prevent collisions [22]. The cameras located on the bridge recorded images of the ships around. Next by grouping pixels and rejecting those which resulted from the sea waves or signal noise the ship patterns were obtained.

In [19, 20] the parameters of airplane motion were determined using visual methods. The data of the scene stored in the system memory was matched with images acquired by the stabilized camera. Next improvements to this approach were proposed to diminish the high computational needs of the system [14]. The camera was not stabilized; and the database of the scene was simplified, which resulted in a slightly better performance of the system. The applicability of visual system was also studied for applications in helicopter flight [1, 4] control. The system using camera mounted under tail boom may be useful to support landing [13, 31].

Visual systems onboard helicopters are used for tracking a ground vehicle. The moving vehicle is represented as a moving group of pixels [30], forming the pattern. Autonomous helicopter flight was controlled by integrated GPS/visual system, used in [16] to detect characteristic shapes of buildings and their parts like doors, windows, etc. Such systems are intended to be applied on UAVs.

Another example of sophisticated application of image processing in aeronautics is autonomous aerial refueling [28, 29]. The imaging sensor is mounted on the fuel probe of the aircraft taking the fuel. The key factor for good system performance is recognition of the configuration of characteristic points matched by LEDs on tanker aircraft.

The image processing methods are applied also to target recognition and tracking [7, 8, 18], used mostly in air-to-air and air-to-surface missiles. The target may be observed both in infrared and in visual part of spectrum of electromagnetic waves.

THE CONCEPT OF VISUAL NAVIGATION SYSTEM

An analytical method is used for pattern matching in this research. Developing the method it was assumed that:

— the same or similar spectral band of radio waves is used during acquisition of images containing characteristic patterns in two cases: for storing the pattern in system memory and during system operation;
— during image acquisition scene visibility and its contents does not vary substantially between subsequent images;
— patterns selected to be recognized in the subsequent images does not change, is not transparent, and it does not change the position with respect to the other objects in the scene;
— before system initialization the image size, approximate size of the pattern and the possibility of overlapping patterns in two sequential images are known.

These assumptions allow to recognize the pattern after scanning the frame. The image matching method applied in this research consists of three phases: image acquisition and preprocessing (edge detection), pattern recognition and pattern matching.

System structure

The block diagram of visual navigation system is shown in figure 1.

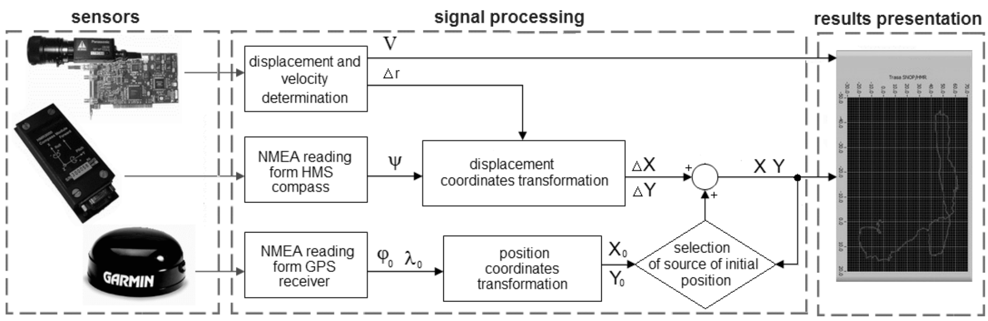

Fig. 1. Visual navigation system

The system contains three sensors: measurement camera, magneto-resistive compass and GPS receiver. Two subsequent images captured by the camera are used for calculating the velocity of the vehicle. The input for velocity calculations is variation of pattern position in two subsequent frames. The position of the vehicle is obtained by dead-reckoning method as a result of integrating the measured velocity. Additional information for calculating position is the heading of the vehicle measured by compass.

The camera and the compass are the only sensors of visual navigation system. They are supplemented by GPS receiver, used for two purposes: to calculate the starting position to initialize the system and to measure the vehicle position for evaluation the accuracy of the position obtained from visual navigation system. The GPS receiver was the most accurate sensor available to verify accuracy of the visual system.

Displacement and Velocity Subsystem

The block diagram of the displacement and velocity subsystem is presented in figure 2.

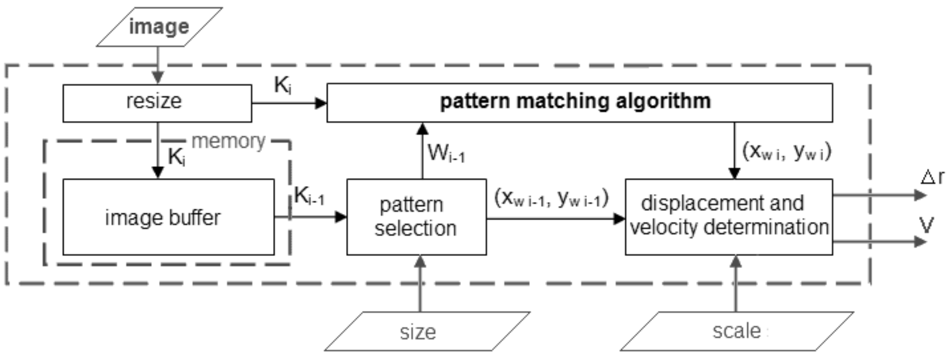

Fig. 2. The displacement and velocity subsystem

A velocity of the vehicle is calculated using variation of a selected pattern position in two subsequent frames. In one time step two operations are performed: recognition of a pattern in the frame captured in the actual time step and selection of the pattern to be recognized in frame in the next time step. A pattern selected for recognition should be identifiable, i.e. it should contain elements which are unique for this particular pattern. Some known a priori constraints of vehicle motion (if any) are helpful in selecting the pattern. The pattern must lie in the part of the frame, which will be found in the frame acquired in the next time step.

A position of a selected pattern is calculated in the local Cartesian system of coordinates OXY of the frame. The origin of local system of coordinates is placed in the left--top corner of the frame. The axes directions are parallel to the frame axes of symmetry.

The coordinates (x_{pi-1}, y_{pi-1}) of a selected pattern P_{i-1} in the frame I_{i-1} recorded in i–1 instant of time are stored in the system memory. The same pattern is searched in the frame I_i. Pattern P_{i-1} and the frame I_i are the input data for the pattern matching algorithm. The details of the matching algorithm are presented in the next section.

The displacements of the vehicle in two perpendicular directions are calculated using coordinates ($x_{p\ i\text{-}1}$, $y_{p\ i\text{-}1}$) of the pattern in $t_{i\text{-}1}$ instant of time and coordinates ($x_{p\ i}$, $y_{p\ i}$) in t_i instant of time (in pixels per second) as:

$$\Delta I_x = x_{W\,i} - x_{W\,i-1}\ ; \tag{1}$$

$$\Delta I_y = y_{W\,i} - y_{W\,i-1}\ . \tag{2}$$

The displacements (1) and (2) are used for calculation of the camera velocity. Due to possible image deformation (which usually occurs in the acquisition process) two orthogonal components of the velocity are calculated separately:

$$V_x = \frac{\Delta I_x \cdot C_x}{\Delta t}\ ; \tag{3}$$

$$V_y = \frac{\Delta I_y \cdot C_y}{\Delta t}\ , \tag{4}$$

where:

Δt — time interval;

C_x, C_y — scale coefficients, describing relations between the displacement of frame (in pixels) and the displacement of camera (in meters); the scale coefficients allow to correct distortion of frame by camera optical system; the method of selection the values of C_x and C_y is discussed in the Field Experiments section.

The equations (3) and (4) present simple, linear relationship between the displacements and velocities of the vehicle and their values measured in the images. This relationship is non-linear. Linear assumption is rational due to the fact that the pattern is two-dimensional and it is equidistant to the camera in subsequent time intervals. The total vehicle displacement and velocity are calculated as:

$$\Delta r = \sqrt{\left(\Delta I_x C_x\right)^2 + \left(\Delta I_y C_y\right)^2}\ ; \tag{5}$$

$$V = \sqrt{V_x^2 + V_y^2}\ . \tag{6}$$

Transformation of Displacement Coordinates

The displacement of the object in the local coordinates system is computed in the block of transformation displacement coordinates using calculated displacement of the camera and the heading:

$$\Delta X = \Delta r \sin(\Psi); \tag{7}$$

$$\Delta Y = \Delta r \cos(\Psi). \tag{8}$$

Then the position of the vehicle is calculated by adding the displacement to the position coordinates calculated in the previous time interval:

$$X = X_0 + \Delta X; \tag{9}$$

$$Y = Y_0 + \Delta Y. \tag{10}$$

The position coordinates X_0 and Y_0 are being taken from calculations of visual system performed in the previous time interval. If another source of position coordinates is present in the system, the coordinates X_0 and Y_0 may be taken from this source.

IMAGE PROCESSING ALGORITHMS

A pattern matching algorithm is usually a time consuming process and it must be carefully selected for the systems operating in real-time. Several image pre-processing methods are used to decrease the computation time.

A frame and a pattern may be resized and the matching process may be performed for the resized data. This method is called *pyramidal matching.* Usually the images are resized using the factor ¼. After determining approximate position of the pattern in the frame, the accurate position is calculated in the frame of a real-size.

Other method of frame pre-processing are *edge detection* or/and *geometric analysis* of the frames. In some cases these methods are more efficient in matching images represented as data in the binary form and to find the edges of the pattern.

In the geometric analysis the simple geometric forms (e.g. circles and lines) are matched to the edges of the pattern in the phase of approximate image matching.

Selection of the algorithms for image acquisition, pre-processing and pattern matching for navigation systems is a difficult, trade-off issue. Application of numerically sophisticated methods increases the chance of calculating the 'exact' solution. But this approach may increase the computation time, which is one of the most important factor in a real-time systems. The way to avoid excessive computation time is to use simple algorithms, but they may have lower accuracy.

During this research the cross correlation algorithm was selected for navigation system due to its capability to perform effective image matching and its relatively low computational time.

The task of the pattern matching algorithm is to identify a location of the pattern in the frame. Usually the matching algorithm maximizes/minimizes the value of specific parameter. A pattern matching algorithm is the core part of a visual navigation system, influencing its accuracy and efficiency.

Calculation of the cross correlation coefficient is the simplest algorithm for comparison of two images of the same size. It was applied in this research due to the requirement for real-time system operation. The correlation coefficient is computed as:

$$\rho = \frac{\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}\left(g_1(x,y)-\mu_1\right)\left(g_2(x,y)-\mu_2\right)}{\sqrt{\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}\left(g_1(x,y)-\mu_1\right)^2\sum_{x=0}^{M-1}\sum_{y=0}^{N-1}\left(g_2(x,y)-\mu_2\right)^2}}, \quad (11)$$

where:
$g_i(x, y)$ — intensity of the pixel at (x, y) in frame i;
x, y — coordinates of the pixel, M, N;
size of the frame in pixels.

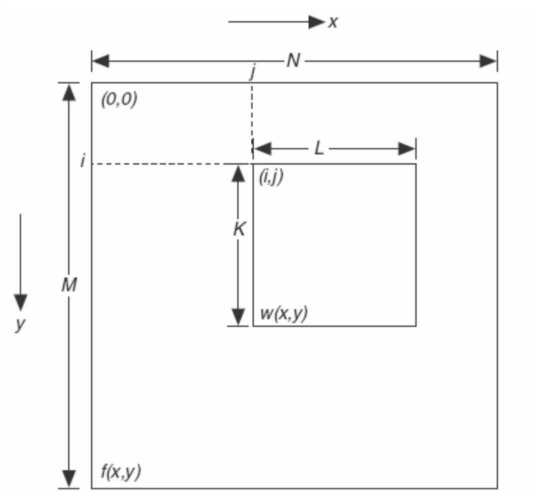

Fig. 3. Block diagram of the displacement and velocity subsystem

The rectangle of $M \times N$ size (in pixels) forms a frame (fig. 3.) where the pattern ($K \times L$) is searched. The best matching of the patterns is achieved when the correlation coefficient $\rho(i, j)$ has the highest value. The value one of the coefficient denotes the best match of images. The values of coordinates (i, j) vary in the range of: $i = 0,1,2,\ldots,M-K$; $j = 0,1,2\ldots, N-L$.

The calculation of cross correlation coefficient may be extended to the case of images of different sizes (big frame and relatively small pattern), by transforming (11) into:

$$\rho(i,j)=\frac{\sum_{x=0}^{L-1}\sum_{y=0}^{K-1}\left(g_1(x,y)-\mu_1\right)\left(g_2(x+i,y+j)-\mu_2(i,j)\right)}{\sqrt{\sum_{x=0}^{L-1}\sum_{y=0}^{K-1}\left(g_1(x,y)-\mu_1\right)^2\sum_{x=0}^{L-1}\sum_{y=0}^{K-1}\left(g_2(x+i,y+j)-\mu_2(i,j)\right)^2}}. \tag{12}$$

In this study the pattern matching algorithm used to obtain the relative displacement of the two frames consisted of the following steps:

1. Frame resizing.
2. Pattern selection.
3. (Alternative) edge detection (Sobel filter).
4. Pattern matching in the subsequent frame.

The efficiency of pattern matching algorithm was evaluated using several scenes represented by various pairs of frames recorded as 768×288 pixels (one of the sample scenes is shown in fig. 4). The frames were recorded using the same hardware as applied later in the field experiments. A selected pattern was identified at the first frame, and then it was searched in the next frame. The evaluation of algorithm efficiency was done for the following cases:

1. Pattern size from 16×16 to 56×56 pixels, with increment of 1 pixel.
2. Pattern resize factors: 1/4, 1/8, 1/12, 1/16.
3. Edge detection applied / not applied.

For each case the correlation coefficient was computed according to (11). The frames were represented as matrices composed of 8 bit integer numbers. Each number represented the intensity of pixel hue. The final result of pattern matching was a calculated location (coordinates i, j) of the pattern in the frame for which the cross correlation coefficient reached its maximum value, i.e.

$$(i,j)=\arg\max_{i,j}\left[\rho(i,j)\right]. \tag{13}$$

Pattern displacements in pixels were calculated and a time of computation in milliseconds was recorded. The true displacement of frames was measured using a standard graphical editor (i.e. MS Paint).

The results of pattern matching for the tested images and patterns are presented in fig. 4–7, where at the abscissa axis is the pattern size and at the ordinates axis is pattern displacement (both axis in pixels). At each figure the results for a specific resizing factor are presented. The dashed lines are the results with application of the edge detection filter and the solid lines are the results without the edge detection.

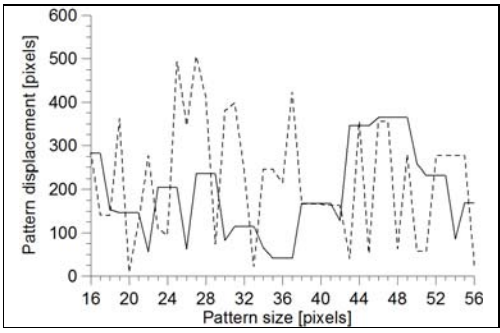

Fig. 4. Displacement calculated for 1/16 resize factor

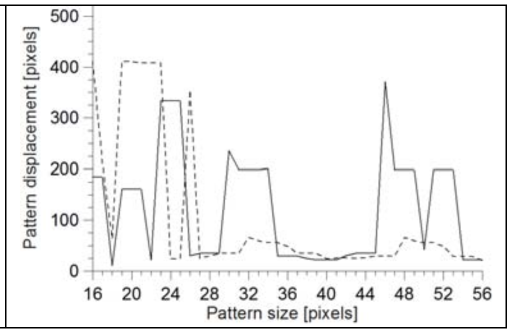

Fig. 5. Displacement calculated for 1/12 resize factor

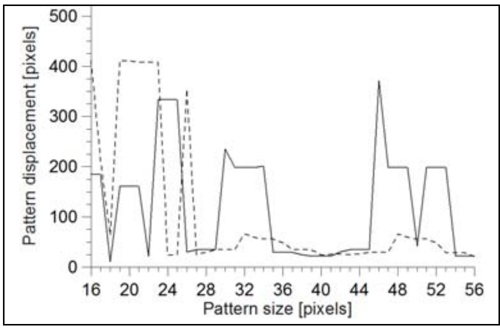

Fig. 6. Displacement calculated for 1/8 resize factor

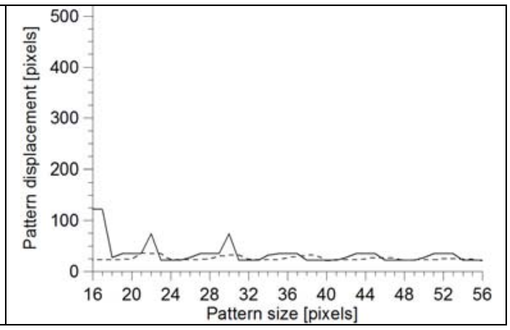

Fig. 7. Displacement calculated for 1/4 resize factor

Figure 4 presents the results for the resize factor of 1/16. The accuracy is far from expected, so the resize factor of 1/16 was not considered in further analysis. In figure 5 results obtained for the resize factor is 1/12 are presented. They prove adequate accuracy for the patterns greater than 44×44 pixels. In figure 6 the results for the resize factor of 1/8 are presented. The real displacement of patterns correlate adequately with the measured by visual method results when the patterns are greater than 32×32 pixels. The results in figure 7 were obtained for the factor ¼. They are adequate for almost all range of pattern sizes. But for this case the computation time varied between 1200 and 3300 milisec which is too-long for a real time navigation system. Therefore, the resize factor of 1/4 was excluded from the further analysis.

From results in figures 4–7 the resize factors of 1/8 and 1/12 were considered in further investigations. The results of computations showed that the edge detection filter did not improved results, and deteriorated efficiency of the algorithm. The computation time is more than 3000 ms for the scale factor of 1/4 and for the size of the pattern of 56×56 pixels, for other scale factors it is less than 500 ms.

The results presented above were used to select a pattern matching algorithm and its parameters for visual navigation system in field tests. The trade-off between algorithm efficiency and computation time led to the following parameters for the-field experiments: pattern size: 56×56 pixels, frames resize factor: 1/8 and 1/12. The computation times for the two frames resize factors were 500 ms and 200 ms respectively.

FIELD EXPERIMENTS

Hardware Configuration

The navigation system described in the previous sections was assembled and tested on an electric cart. The following hardware was used: camera (Panasonic GP-MF622), frame grabber (National Instruments NI-1407), magnetoresistive compass (Honeywell HMR 3000), computer (PC Pentium III 500 MHz), GPS receiver (Garmin GPS 16A), power supply devices. The data from the sensors were acquired with the frequency of 5 Hz. The cart with mounted power supply and navigational hardware is shown in figure 8.

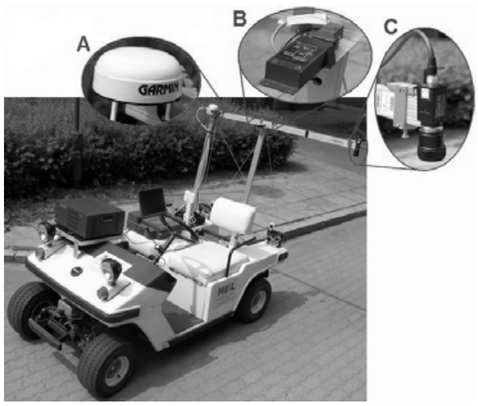

Fig. 8. Electric cart with navigational hardware

Results of Field Experiments

The objective of the field experiments was to evaluate effectiveness of the visual navigation system: hardware and software. The system was calibrated first and then the effectiveness of velocity and position measurement was determined.

In all the experiments the pattern size was 56×56 pixels. The time step of Δt = 600 [ms] was selected based of the requirement of maximal computation time (up to 500 [ms]) for pattern matching algorithm. The time increment Δt should be integer multiple of the time interval of hardware sampling. The edge detection filter was not applied.

The aim of system calibration was to determine the scale coefficients C_x, C_y describing the ratio of frame displacement in pixels to camera displacement in meters. The system calibration was done by two methods: the manual method, and the velocity method. In the manual method the scale coefficients were obtained by measuring the size (in frame coordinates) of the static, flat object of known size. In the velocity method, the system (camera) was moving. The velocity (in the frame x axis) measured by camera was compared with the velocity provided by GPS receiver. The coefficient C_x was calculated form (3), as:

$$C_x = \frac{V_x \cdot \Delta t}{\Delta K_x} \quad (14)$$

The size along the y axis of the image recorded by the camera was the half of the size along x axis, so the coefficient C_y was calculated as:

$$C_y = 0.5 \cdot C_x \quad (15)$$

The comparison of the scale coefficients calculated by manual and velocity methods is presented in figure 12. The coefficients obtained from manual method shown as dashed lines in figure 12 were: C_x = 480, C_y = 240. The values of the coefficients obtained by velocity method were C_x = 513 (for 1/8 pattern resize factor, left-side graph) and C_x = 448 (for 1/12 pattern resize factor, right-side graph). They are shown in figure 9 as solid lines. The relative error of scale coefficients computation by velocity method is 6,9% and 6,7% respectively.

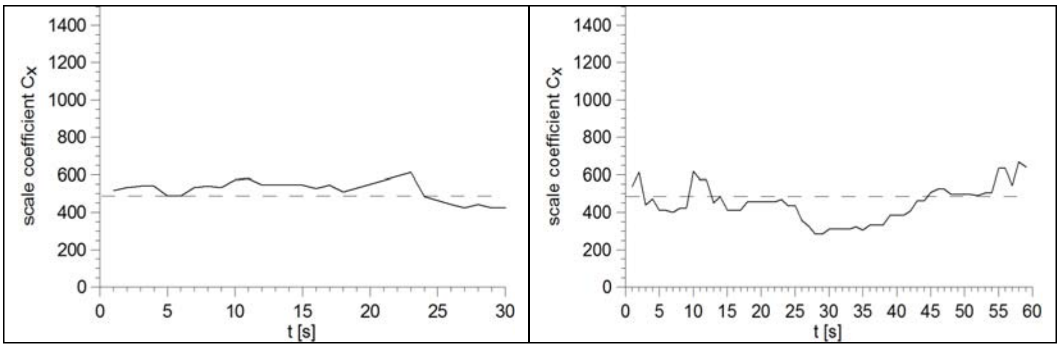

Fig. 9. Scale coefficient C_x

The calibration results proved effectiveness of the both: manual and velocity methods. The velocity method is useful, when there is no possibility to calibrate the system manually. The adequate efficiency of this method is important, because in many applications the distance between the camera and the scene may be not known.

In the second part of the field experiments the velocity of the vehicle was measured by visual navigation system and compared to the values measured by GPS receiver. The GPS receiver was used as a reference sensor, and for each time step the relative velocity error was calculated as:

$$\varepsilon_V = \frac{V_{GPS} - V_{VISUAL}}{V_{GPS}} \cdot 100\% \,. \tag{16}$$

The computations were for constant distance (1.66 m) between the camera and the scene. The scale coefficient was C_x = 480, the value obtained by manual method. During experiments the cart was moving with approximately constant speed. The results of velocity measurement are shown in fig. 10 for the pattern resize factor of 1/8 and 1/12.

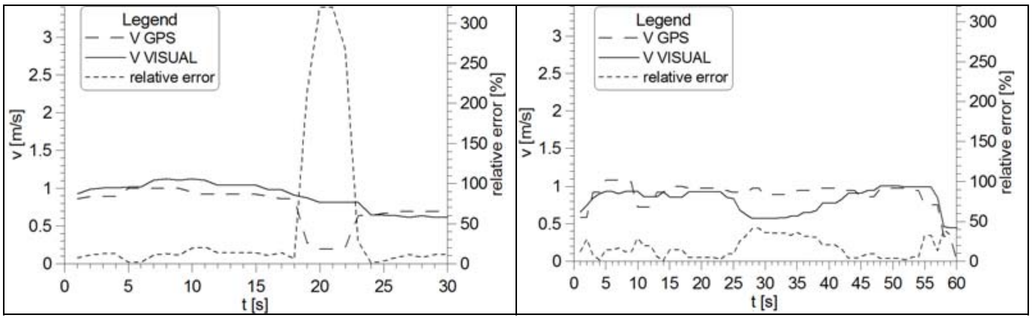

Fig. 10. Velocity measured by visual system compared to GPS results

For value 1/12 of pattern resize factor the relative velocity error is greater then 30% in many instants of time. For the factor of 1/8 the velocity error was less then 20% (except short period of GPS operation discontinuity). From these results it was concluded, that the algorithm with pattern resize factor of 1/8 was the most effective and it was selected for position determination.

Next the tests were carried out to verify the results of the selected pattern resize factor. The velocity measured during acceleration and deceleration of the cart is presented in figure 11.

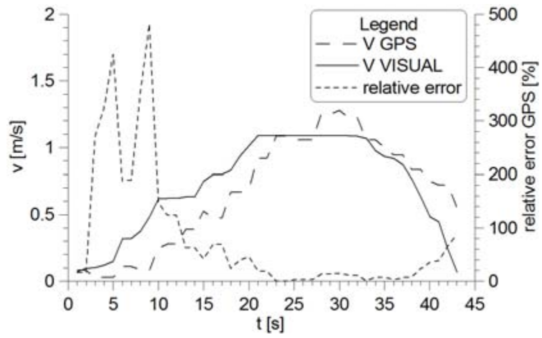

Fig. 11. Velocity during accelerating and decelerating of the cart

The relative velocity error was less then 10% in time, when the cart velocity was approximately constant. The velocity error was greater when the vehicle accelerates; the velocity increases or decreases. The reason of this results is time delay velocity measurements by GPS. The large values of the error in the initial phase of the measurement are supposed to be the result of the numerical noise.

The last phase of field experiments was investigation of the visual system supported with magnetic compass and GPS. The pattern resize factor was 1/8. The cart trajectory for two scenarios is shown in figure 12. In figure 12a the vehicle trajectory is presented for the case when the visual system was corrected by GPS in every 12 s. In the second graph (denoted on graphs as resetting time $T = \infty$) no GPS correction was applied. Solid lines present the trajectory according to visual system and dashed lines according to GPS.

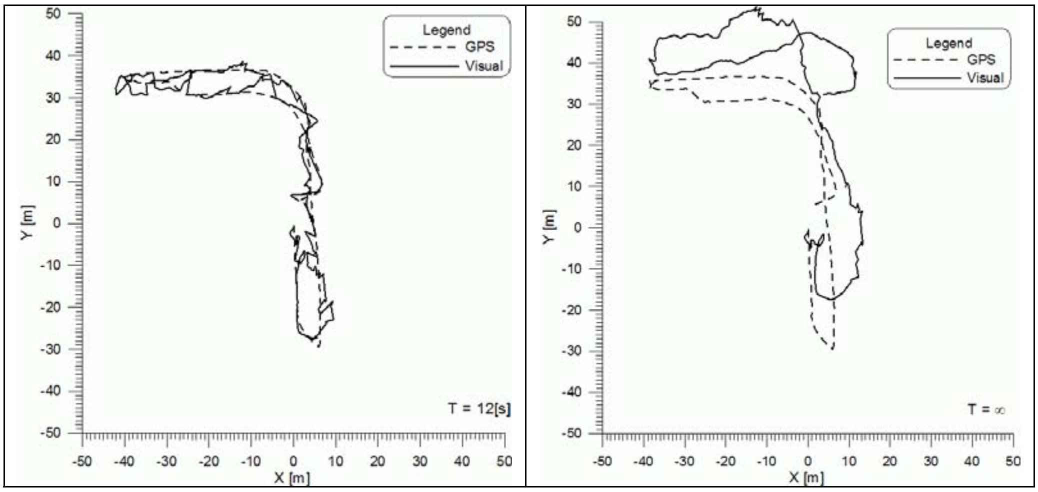

Fig. 12. Cart trajectory according to visual system and GPS

The relative position errors of visual system are shown in figure 13 for the correction frequencies as in figure 12. The error was computed as:

$$\varepsilon_{POS} = \sqrt{\left(X_{GPS} - X_{VISUAL}\right)^2 + \left(Y_{GPS} - Y_{VISUAL}\right)^2} \ . \tag{17}$$

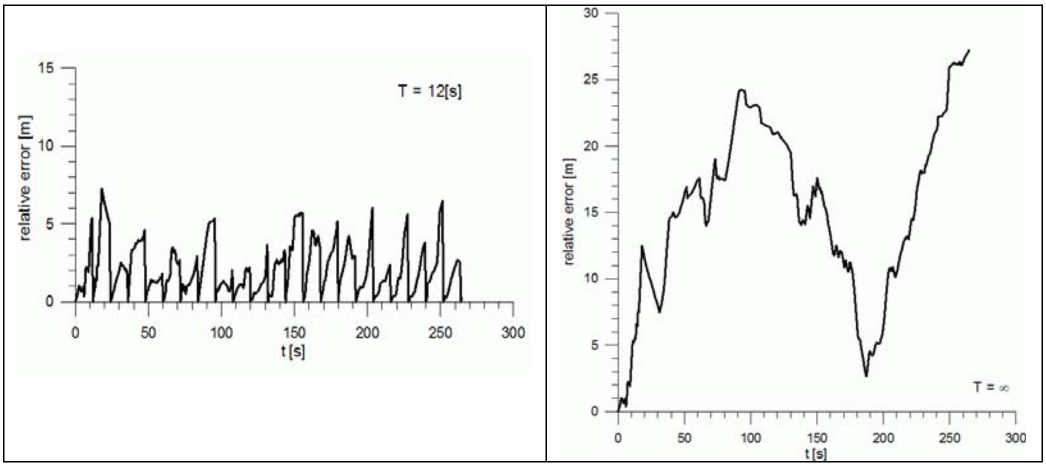

Fig. 13. Relative position error of visual system

The results obtained in the field tests proved the necessity of integration of the visual navigation system with the other systems for achieving the acceptable accuracy. Visual navigation system supported by GPS seems to be the effective solution. In GPS/Visual integrated system, the visual method is applicable, when the GPS receiver produces large errors or the signal is not available.

CONCLUSIONS

The main goal of the research presented in this paper was to investigate the feasibility of designing visual navigation system based on the affordable visual camera and elementary image processing algorithms. The advantages of this concept are potential adequate accuracy, autonomous work and independence of radio navigation signal, as well as any other external, artificial signals.

The Scene Matching Area Correlation (SMAC) method was selected for application to visual positioning. The first step of this process is a pattern matching algorithm. During the laboratory tests, the cross correlation algorithm was selected to be core of navigation algorithm. The values of algorithm parameters were adjusted by computations and experiments.

The concept of visual navigation system composed of typical measurement camera and supported with magnetoresistive compass and GPS receiver was elaborated, designed and assembled. The system was tested in in-field experiments on electric cart. It may be concluded from the experimental research that:

1. The system has satisfactory accuracy level for many applications.
2. The high performance of the system is a result of properly selected and adjusted pattern matching algorithm.
3. The integration of the visual system with other, mostly non-autonomous positioning systems significantly improves system efficiency.
4. Non-expensive on-shelf devices and simple algorithms give adequate results for many applications.

The visual navigation system may be applied on-board of mobile vehicles, as an autonomous system or supplementing GPS, when no satellite navigation signal is available. The visual navigation system may also be used for monitoring the integrity of satellite navigation system. The disadvantage of the visual methods is time-consuming algorithms for image processing, especially when not powerful computers or simple algorithms are used.

There are some issues that need to be addressed in the further research. A system with the camera only used as a sensor may be may be designed by improving the visual algorithm, adding capability of estimating the angular displacement of the vehicle. The other improvement would be autonomous calibration method.

REFERENCES

[1] Amidi O., Mesaki Y., Kanade T., Uenohara, M., Research on an Autonomous Vision Guided Helicopter, Fifth World Conference on Robotics Research, September 1994.

[2] Biezad D. J., Integrated Navigation and Guidance Systems, AIAA, Reston 1999.

[3] Bose T., Chen M., Meyer F. G., Digital Signal and Image Processing, John Wiley & Sons, Hoboken 2004.

[4] Bosse M., Karl W. C., Castanon D., DeBitetto P., A Vision Augmented Navigation System, IEEE Conference on Intelligent Transportation Systems, Boston 1997.

[5] Bow S., Pattern Recognition and Image Preprocessing, 2nd ed., Marcel Dekker, New York 2002.

[6] El-Rabbany A., Introduction to GPS: the Global Positioning System, Artech House, Boston 2002.

[7] Evans J. S., Evans R. J., Image-enhanced Multiple Model Tracking, Automatica, 1999, Vol. 35, No. 11, pp. 1769–1786.

[8] Farooq A., Limebeer D. J. N., Trajectory Optimization for Air-to-Surface Missiles with Imaging Radars, AIAA Journal of Guidance, Control and Dynamics, 2002, Vol. 25, No. 5, pp. 876–887.

[9] Farrell J. A., Barth M. J., The Global Positioning System and Inertial Navigation, MacGraw-Hill, London 1999.

[10] Ferruz J., Ollero A., Integrated Real-Time Vision System For Vehicle Control In Non-Structured Environments, Engineering Applications of Artificial Intelligence, 2000, Vol. 13, No. 3, pp. 215–236.

[11] Ferruz J., Ollero A., Real-Time Feature Matching In Image Sequences For Non-Structured Environments. Applications To Vehicle Guidance, Journal of Intelligent & Robotic Systems, 2000, Vol. 28, No. 1/2, pp. 85–123.

[12] Franke U., Gavrila D., Gern A., Gorzig S., Janssen R., Paetzold F., Wohler Ch., From Door to Door — Principles And Applications of Computer Vision for Driver Assistant Systems, Intelligent Vehicle Technologies: Theory and Applications, ed. by L. Vlacic, M. Parent, F. Harashima, Butterworth-Heinemann, Oxford 2001, pp. 131–188.

[13] Garcia-Pardo P. J., Sukhatme G. S., Montgomery J. F. Towards Vision-Based Safe Landing for an Autonomous Helicopter, Robotics and Autonomous Systems, 2001, Vol. 38, pp. 19–29.

[14] Gurfil P., Rotstein H., Partial Aircraft State Estimation from Visual Motion Using the Subspace Constraints Approach, AIAA Journal of Guidance, Control and Dynamics, 2001, Vol. 24, No. 5, pp. 1016–1028.

[15] Hofmann-Wellenhof B., Lichtenegger H., Collins J., Global Positioning System: Theory and Practice, Springer — Verlag, Wien 2001.

[16] Johnson E. N., Proctor A. A., Ha J., Tannenbaum A. R., Viusal Search Automation for Unmanned Aerial Vehicles, IEEE Transactions on Aerospace and Electronic Systems, 2005, Vol. 41, No. 1, pp. 219–232.

[17] Kayton M., Fried W. R., Avionics Navigation Systems, John Wiley, New York 1997.

[18] Malas J. A., Pasala K. M., Westerkamp J., Automatic Target Classification of Slow Moving Ground Targets in Clutter, IEEE Transactions on Aerospace and Electronic Systems, 2004, Vol. 40, No. 1, pp. 190–205.

[19] Merhav S. J., Bresler Y., On-line Vehicle Motion Estimation From Visual Terrain Information, Part 1: Recursive Image Registration, AES-22, 1986, Vol. 9, No. 5, pp. 583–587.

[20] Merhav S. J., Bresler Y., On-line Vehicle Motion Estimation From Visual Terrain Information, Part 2: Ground Velocity and Position Estimation, AES-22, 1986, Vol. 9, No. 5, pp. 588–604.

[21] Pratt W. K., Digital Image Processing, 3rd ed., John Wiley & Sons, New York 2001.

[22] Shimpo M., Lu Y., Oshima M., A Detection Method of Moving Ship from Navigational Image Sequence, 11th World IAIN Congress: Smart Navigation — Systems and Services, Berlin 2003.

[23] Shinmoto Y., Vehicle Optical Sensor, Intelligent Vehicle Technologies: Theory and Applications, ed. by L. Vlacic, M. Parent, F. Harashima, Butterworth--Heinemann, Oxford 2001, pp. 87–112.

[24] Stateczny A., Comparative Navigation as an Alternative Positioning System, 11th World IAIN Congress: Smart Navigation — Systems and Services, Berlin 2003.

[25] Stateczny A., Comparative Navigation (in Polish), The Scientific Society of Gdańsk, Gdańsk 2001.

[26] Stiller Ch., Towards Intelligent Automotive Vision Systems, Intelligent Vehicle Technologies: Theory and Applications, ed. by L. Vlacic, M. Parent, F. Harashima, Butterworth-Heinemann, Oxford 2001, pp. 113–130.

[27] Tuzlukov V. P., Signal Processing Noise, CRC Press, Boca Raton 2002.

[28] Valasek J., Kimmett J., Junkins J. L., Autonomous Aerial Refueling Utilizing a Vision Based Navigation System, AIAA 2002-4469.

[29] Valasek J., Kimmett J., Junkins J. L., Hughes D., Gunnam K., Vision Based Sensor and Navigation System for Autonomous Aerial Refueling, AIAA 2002-3441.

[30] Vaughan R. T., Sukhatme G. S., Mesa-Martinez J., Montgomery J. F., Fly Spy: Lightweight Localization and Target Tracking for Cooperating Ground and Air Robots, Proc. Int. Symp. Distributed Autonomous Robot Systems, Knoxville 2000.

[31] Wells G., Venaille C., Torras C., Vision-Based Robot Positioning Using Neural Networks, Image and Vision Comput., 1996, Vol. 14, pp. 715–732.

[32] Zasuwa M., Narkiewicz J., Application of Image Matching Navigation System to Support Approach and Landing of VTOL Vehicle, The International 58th Annual Forum and Technology Display, Montreal 2002.

Received October 2008
Reviewed November 2009