Vision System for Relative Motion Estimation from Optical Flow

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ABSTRACT
For the recent years there was an increasing interest in different methods of motion analysis based on visual data acquisition. Vision systems, intended to obtain quantitative data about motion in real time are especially in demand. This paper is about the vision systems that allow receiving information regarding relative object motion in real time. It is shown, that the algorithms solving a wide range of practical problems by definition of relative movement can be generated on the basis of the known algorithms of an optical flow calculation. One of the goals of the system in question is the creation of economically efficient intellectual sensor prototype for the estimation of relative objects motion based on optic flow. The results of the experiments with a prototype system model are shown. This research was supported in part by the grant of RFBR № 08-01-00908.

Keywords: vision system, optical flow, relative motion, open libraries, component approach, contactless odometer.

1. INTRODUCTION
Works in the field of an optical flow calculation have been conducted for more than 30 years. Last decade these methods became accessible to application in a wide range of applied problems due to increase of computers computing capacity and the occurrence of specialized graphic processors. There are many articles written devoted to the description and application of optical flow methods [1-17]. There are also widely available libraries with an open code in which the ready realizations of the most popular optical flow methods can be found (for example, OpenCV [18], LTI-Lib [19], VXL [20]). Methods of optical flow appear suitable for segmentation of images [15], and also for detection of obstacles from moving objects [3].

Despite of increasing capacity of computer complexes and machines, it is important for a considerable quantity of applications to find out the possibility to apply accessible realizations of an optical flow method at small computing expenses and with the preservation of sufficient accuracy and stability of calculation to the given application. In methods of an optical flow calculation and processing the use of some restrictions is possible to reduce computing expenses.

Actual questions are:

• the accuracy of calculations at the low image resolution;
• the optimal parameters values selection of an optical flow method for specific targets;
• questions of algorithms construction which adjust parameters depending on changing conditions.

In the described work the problems were:

• The calculations and interpretations of an optical flow by Lucas-Kanade method on the pyramids of images at the plane-parallel camera movement and the movement under an angle to an observable plane;
• Researches on the dependence of calculation accuracy to the values of algorithm parameters in various applied tasks;
• The support of work of all algorithms in the real time scale.

The KIAM RAS template of the real time vision system program VSSoftware [21] and specially made hardware-software complex for studying the parameters of Lucas-Kanade optical flow on pyramids of images and feature points allocation methods were used to solve the problem/ existing in KIAM laboratory of vision systems. VSSoftware represents the modular, multiline application which allows to realize quickly various algorithms of visual data processing, first of all the algorithms of work with Lucas-Kanade optical flow, and to investigate its adjusted parameters.

The offered solutions have been tested on several practical tasks (see item 3) by means of prototype VS model: the VS for relative movement estimation on the optical flow, created in KIAM VS laboratory.

2. VISION SYSTEM FOR RELATIVE MOTION ESTIMATION FROM OPTICAL FLOW

ARCHITECTURE

At VS creation two basic methods were used for the definition of relative movement on an optical flow:

• COTS technology in configuration of hardware and software system parts;
• the component approach to real time VS design.

Besides, the VS system was formed as a component of supply system with the information of mobile devices and within it the possibility of integration with systems of local and global navigation, in particular, was put.

Software

Methods of the sparse optical flow have been applied to achieve the peak efficiency and to decrease the computing expenses. The optical flow is being searched not on all image, but only in the points which have certain features [5, 6, 7, 13].

Work of any algorithm based on the method of the sparse optical flow consists of three stages: the allocation of particular areas (characteristic points of the image), the combination of images (definition of the vectors of characteristic points displacement), the segmentation of the received vector field and its interpretation. We will name these stages as the levels of processing of the source visual data. To these traditional operations the algorithms of a choice of regions of interest in
video cameras fields of view and the algorithms of statistical processing of the calculated vectors of displacement and the algorithms of an automatic change of parameters of entrance visual data were added.

**Low level algorithms**
The functions from OpenCV library [18] were used as a complete implementation of the bottom level of processing of video data. The approach on the basis of the feature points extraction was chosen in order to maintain the system work in real time and to have a possibility of operative adjustment for new problems or on a fast scene change at a low level from the known optical flow methods [11, 14]. Possibility of progressive processing of image points - by regions of interest. These regions are set by special masks (on the basis of the apriority information or defined by results of the analysis of the video sequence previous images) formed algorithms of top level.

**Feature points allocation.** Let each point of the image be characterized by the function of intensity \( f(x, y) \). As the characteristic points, for the further combination angular points are taken. Harris's [6] modified algorithm which reacts to angles is applied to their allocation. For the angle in this case the local maxima of \( I(x, y) \) values of the function of response algorithm. As several next points of an angle give the maximum the high-frequency filtration has already been contained in the numerical methods) are in a vicinity of points, therefore their allocation. For the angle in this case the local maxima of \( I(x, y) \) values of the function of response algorithm. As several next points of an angle give the maximum the high-frequency filtration has already been contained in the numerical methods) are in a vicinity of points, therefore there’s no point of applying the algorithm of an optical flow to such points. To combine the images, i.e. to find the displacement vector, the Lucas-Kanade method is applied from which the condition of minimization follows that the displacement vector:

\[
\nu_{opt} \approx G^{-1}b
\]

The formula (3) is the basic formula of Lucas-Kanade optical flow, tells that the vector which fully correlates a point of the first image to a point of the second can be found with a margin error. To reduce this error the given method is applied iteratively, i.e. the found vector is the algorithm input parameter for finding a new, more exact one, and the operation repeats until the achievement of the certain accuracy or the quantity of iterations. The methods of an optical flow have an essential weakness: they can be applied at small (1-3 pixels) displacement of objects. To find the bigger displacement, the algorithm should be applied to the Gaussian pyramid of the initial image. At first, the vectors at the uppermost level of a pyramid are calculated; the result is being specified until it reaches the errors number sufficient for application at the following (lower) level of a pyramid. The stages of calculations are repeated for all levels. At the last level comes the vector of an optical flow. This algorithm with all its advantages has an essential weakness: the small mistake at calculations at the pyramid top level tends to accumulate and increase.

In the OpenCV implementation depending on flags, the pyramid of images can be constructed in advance, or the function of the finding of an optical flow will cause it before the calculation begins. The size of a pyramid is taken out of proceeding from a rough estimate of visible plane-parallel displacement of the image (or from the prior information, or the previously calculated vector). Each new level of a pyramid allows finding the displacement twice as big as previous.

If the feature point of the first image appears closed on the second or goes out of the image area, the two variants are available: either such point is marked as the point for which a conformity is not found, or the algorithm will put another in conformity, with the similar signs to put the false vector (i.e. a vector mismatching the true movement of the objects of a scene) an optical flow. The false vectors will be filtered at the next stage of the algorithm.

**The false vectors filtration.** Depending on the certain application, the filtration of the vectors can represent more of a
challenge, than a direct finding of an optical flow. Undoubtedly, the accuracy and the stability of the solution of a specific task will depend from the stage of segmentation of vectors of an optical flow. Also at the given stage the image comparisons in a chamber objective (the so-called visible image) to the real movement of the chamber (objects concerning the chamber) occur, and the obtained data will serve as the estimation for the algorithms adjustment in calculations on the subsequent shots.

At a described stage of research, the relative movements, in which the visible movement was either the plane-parallel movement or the movement (a plane of a sensor control of the chamber) under a constant angle to a surface plane, were considered.

It is quite easy to find an average vector for an optical flow of such camera movement. Which vector of co-ordinate is equal to the sums of corresponding co-ordinates of all vectors divided to a quantity of vectors (considering the corrections of the chamber movement under an angle).

The filtration of the false vectors of an optical flow is expedient to apply in a direction or length, keeping those, directions or which lengths lay in a limit of the chosen error of definition of an average vector. The given filtrations can be applied iteratively: find an average vector, reject the vector with the considerable deviations of directions or lengths from an average, among the found search for a new average vector, reject, and reducing an error. So the accuracy of the calculation of an average vector (with a reference to the plane-parallel movement) rises. As the restrictions to the chamber movement, are set a priori, so it becomes possible to receive the movement parameters directly, comparing an average vector to the real world metrics.

**Top-level algorithms**

The target task of top-level algorithms – the relative motion estimation – is divided into several subtasks:

- selection of the relative motion model;
- the model verification/specification;
- calculation of relative motion quantitative characteristics.

Under the fixed functioning conditions the part of these subtasks can be passed.

For example, in a mode of functioning as contactless odometer, it is possible to consider, that the scene scale is fixed, and the motion model is limited by the kinematic scheme of a vehicle or the robot. Then the decision of the first subtask is replaced with use of an aprioristic set of motion models. Similar simplification is applicable and in case of estimation of the inspection tool movement under a processed surface by mechanical machining.

Mathematical models describe a priori certain type of relative motion and can change operatively on signals from the outside or by results of the current visual scene analysis. Besides, these models can consider the model of the vehicle on which the acquisition device is mounted. For example, it can be model of a car suspension, allowing to correct the image scale on the next analyzed video sequence image.

Top-level algorithms are developed with the original approach to the images analysis on the basis of a combination of “top-bottom” and “bottom-top” methods [21, 22].

**The hardware.**

The structure of the system is modular and open:

- One or several acquisition devices (a video camera with optical system) + the input channel for the image transfer into the computing-control device.
- The computing-control device (universal computer or specialized computing device).
- Software (mathematical models; top-, middle- and low-level algorithms).

The VS is composed in a following way. Different types of videocameras with various lenses were used as acquisition devices, as well as inexpensive analogue videocameras with framegrabber or TV-tuner, digital Web-cameras and more expensive Ethernet cameras such as those with progressive scan. Notebook and barebones systems were used for computing and control.

The VS architecture has been tested on the contactless odometer prototype model (fig. 1).

![Fig. 1. General view of prototype model components of the navigating system including contactless odometer. 1 – the videocamera on fixing platform; 2 – the computing and control unit; 3 – the three-dimensional accelerometer; 4 – the single-dimensional accelerometer; 5 – the GPS-receiver antenna; 6 – the power converter block.](image)

3. **EXPERIMENTS WITH A SYSTEM PROTOTYPE MODEL.**

**Mobile robots**

The results of the research of VS for contactless estimation of movements were tested for the information support improvement of two mobile robots: MRK-27 and “Trikol”.

**Remotely controlled robot MRK-27** (CKTB PR Moscow State Technical University of a name of Bauman N.E.) (fig. 2) – the small-serial robot on the track-type chassis. It is actively used in many applied tasks.

The field of view «under feet» has been used in experiments with this robot. It provided the exact and fast estimation of the robot movement. The results data can be used in a robot control contour. The robot movements took place on a smooth concrete floor with the speed of about 1 m/s. The movement trajectories were rectilinear and curvilinear. Distances of 10-30 m have been fixed by contactless odometer to about 0,01 m (fig. 3).

![Fig. 2. The registering block of the contactless odometer is mounted in a MRK-27 grasping unit.](image)
On fig.3 the example of the displacement vectors detection for concrete floor scenes is shown. Frequency of the displacement vector generation is not less than 10 Hz.

“Trikol” is a laboratory maneuverable three-wheeled robot with the high autonomy capability (fig. 4).

Railway transport

The fields of views of the computer vision systems intended for an inspection and measurements of parameters of various railway infrastructure objects were used in experiments. The regions of interest in these fields of view were allocated automatically. In these regions the estimation of movement of rolling vehicles relating railway was made. So, for the way reckoning by visual data from a field of view intended for the control of a ballast section (fig.6), rails threads were extracted, and relating to them the regions for an optical flow calculation and for the movement vector estimation were located.

In another system designed for the rail ties surface and rail joints control, the search of railroad ties was performed at first in the field of view. Then relative to them regions of interest were positioned. The calculation of an optical flow and estimation of movement vectors was made in them.
Fig. 8. The movement vectors estimation based on areas of a railroad ties lattice along rail threads in a field of view intended for the rail joints control (speed of movement of 15-20 m/s).

Fig. 9. The movement vectors estimation based on areas of a railroad ties lattice along rail threads in a field of view intended for the railroad ties control (speed of movement of 15-20 m/s).

In all listed systems the specified restrictions on move speed were defined by the cameras intended for the inspection of rather large objects instead of that special videocameras. These cameras correspond to the TV standard. The use in the same configuration of progressive videocameras and a selection of local regions of interest allows to provide the solution of a movement estimation problem of a rolling stock with the speed up to 250 km/hour and accuracy 0.02% (% from a way) (by visual data from a forward looking field of view) and to 120 km/hour and accuracy 0.01% (% from a way) by visual data from a «under feet» field of view.

Motor transport

The contactless odometry task is actual for various mobile laboratories for which the exact measurements binding is essentially important. The described VS has been tested as a part of mobile laboratory for operative diagnostics of a road surface. There are several videocameras for the various parameters of a road surface control in this laboratory. The field of view of the forward looking camera has been chosen for the experiments on contactless odometry (fig. 10).

Fig. 10. The general view of the mobile laboratory for operative diagnostics of a road surface (MLOD). The arrow specifies the forward looking videocamera.

Fig. 11. The movement vectors estimated at the MLOD mobile laboratory movement on wet asphalt road with 2-9 m/s speed.

On fig. 12 the closed trajectory of the robot movement is presented. This trajectory restored according to contactless odometer measurements.

Fig. 12. A trajectory of the MLOD laboratory movement. It is constructed according to the contactless odometer measurements by results of a circular route tour. At a circular route of 195 m length, an error of the moving estimation was 0,5 m.

Machining process

The actual example of a demand of contactless relative movements estimation of other scale is an example of movement measurements of the inspection tool. It is required to be made in the process of the operative quality control of a processed surface by mechanical machining. In this task the measuring head moves on 10 mm distance from a processed surface. The size of a controllable field of view is 10x10 mm. Two relative movement components find reflection in an optical flow: horizontal and vertical, differing more than on two orders. The head of the processing tool on which the videocamera is fixed, moves along a processed detail (diameter 30-60 cm, rotate with a speed of 15-30 revo) in a horizontal direction with a speed 3-30 cm/min.

Algorithms of the top level considering model of relative movement, adjusting parameters of the low level algorithms and make possible to allocate an interesting horizontal component of speed (fig. 13). It is executed in
parallel with the main inspection processing. And in this task, described VS showed good results.

Fig. 13. Vectors of horizontal displacement, calculated on field of view of a measuring head moving under processed surface.

4. CONCLUSION

The rational use of well-known low-level optical flow algorithms can provide the successful solution of a wide range of applied tasks to estimate the parameters of relative objects movement and that is shown in the described research on the series of experiments.

Thus, a number of problems of the optical flow analysis were overcome:

- big volume of processed data;
- texture variability (the structure of an underlying surface);
- errors in feature points correspondences.

The used hardware and software means make the offered solutions economically attractive.

Cost of the equipment used in the majority of considered configuration variants made an order of 1500-2000$. For variants automobile and railway contactless odometers, capable to work on speeds more than 60 km per hour this cost increases approximately in 2 times (for the account of high-speed videocameras with progressive scan).

The production of the special low-level software allows to reduce the optical flow computing cost and to provide optimization on an overall performance of the system of relative objects movement estimation based on an optical flow.

The following steps in development of the described approach are:

- the estimation of complex rotary movements of mobile objects (roll, pitch, yaw) based on optical flow;
- the fusion and sharing of data of relative movement from the optical flow channel with other local navigation systems, such as the vertical sensor and accelerometer-based local navigating system;
- the development of methods for an adaptive adjustment in uncontrolled light conditions (in considerable limits).

5. REFERENCES