Tests of Monitoring of Motion Variables of Unmanned Vehicle Convoy

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Abstract*:This work analyzes test results of motion control system of unmanned cargo vehicles convoy with manned master vehicle developed by NAMI Institute. Development of intelligent transportation systems is determined by necessity to improve efficiency and safety of cargo and passenger traffic in hard-to-reach areas of northern Russia, Arctic and Antarctic regions. Scientific substantiation of engineering solutions accounting for specific operation conditions and peculiarities of controls is of outstanding importance. The problem of motion control of unmanned vehicle convoy is formulated in terms of dynamic stability of state coordinates, its solution prevents collision with obstacles and stability control of master vehicle. State coordinates of vehicles were determined by virtual data sensors based on indirect measurements using mathematical models and solution algorithms of ill-posed problems. Measurements of longitudinal speed of mass center, longitudinal and transversal accelerations, pressure drop in tires, turning angle of driven wheels, motion path plotting and recognition of road markings have been analyzed. Efficiency of the developed system of motion control of unmanned vehicle convoy in Russia has been confirmed experimentally.

***Keywords*: motion control system, unmanned vehicle convoy, problem of dynamic stabilization, virtual data sensors.**

I. INTRODUCTION

Provision of better intercommunications between Russian regions by means of intelligent transportation systems is based on development of innovative types of unmanned cargo vehicles facilitating significant improvement of efficiency and safety of cargo and passenger traffic in hard-to-reach areas of northern Russia, Arctic and Antarctic regions.

Possible improvement of efficiency of cargo and passenger traffic [1] due to elimination of negative impact of human factor, road accident reduction and increased capacity of vehicles determines increased interest of car manufacturers to advances in the field of unmanned vehicles.

In recent decades the leading Western companies [2] gained significant experience in the field of intelligent transportation systems [3] and unmanned vehicles.

In terms of modern control theory, the problem of automatic control of unmanned vehicle is reduced to dynamic stabilization of state variables, which prevents collision with obstacles and improves stability control.

The state variables are as follows: longitudinal speeds of mass centers, longitudinal and transversal accelerations, turning angles and longitudinal slides of wheels, pressure and temperature of tires and brakes, distance to obstacles in traffic lanes, and others.

Monitoring of state variables is supported by specialized sensors of physical variables, computer vision systems [4] based on radars, lidars, video cams, as well as satellite [5], inertial [6], and odometric [7, 8] navigation systems.

Road and climatic conditions of Russia are characterized by periods with low temperatures up to –40°C, limited roadway network with hard surface, unavailability of recognizable road markings, significant roughness of road surface, minimum number of traffic lanes, restricted visibility during polar nights and existence of ice and snow on the roads in winter and spring–autumn seasons [9, 10].

Under such conditions, foreign anti-lock braking systems and stability control systems on their basis are insufficiently efficient.

Application of computer vision systems for monitoring vehicle position on the road, determination of distance to obstacles, and recognition of road markings is restricted by illumination, precipitations, fog, and visible markings.

Application of satellite navigation systems is restricted by conditions of radio vision in forest arrays, tunnels, and state of Earth's troposphere, etc.

Advanced system of motion control of cargo vehicle convoy with manned master vehicle is based on innovative solutions of monitoring of state variables, navigation, and control of traction, brakes, and path.

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II. PROPOSED METHODOLOGY

A. General description

Dynamic stabilization of vector X of state coordinates of controllable objects is reduced to meeting the requirements of the set of inequalities:

$$X_{\mathrm{ilim}}^{L}(U,X,t) \le x_i(t) \le X_{\mathrm{ilim}}^{U}(U,X,t), 1 \le i \le n \text{ at } U \in U_{\mathrm{supp}} \quad (1)$$

where $x_i(t)$ is the i-th component of state vector X; $X_{\mathrm{ilim}}^{L}(U,X,t)$ is the lower limit of allowable x_i ; $X_{\mathrm{ilim}}^{U}(U,X,t)$ is the upper limit of allowable x_i ; $U = (U_1, U_2, U_3, U_4)^T$ is the vector controllable actions on gearbox (U_1), engine traction (U_2), brakes (U_3) and steering (U_4).

Upper and lower limits of allowable coordinates of state depend on controlling action, full vector of state and time which renders dynamic properties to the limits.

Solution of the problem of state dynamic stabilization is sought for estimated $\hat{x}_i$ and estimated upper and lower limits $\hat{X}_{\mathrm{ilim}}^{L}(U,X,t)$ and $\hat{X}_{\mathrm{ilim}}^{U}(U,X,t)$. This implies rigid restrictions both on proximity of estimated $\hat{x}_i$ and their actual values x_i, and on proximity of estimated limits and their actual values. It is unacceptable when the problem of dynamic stabilization of state coordinates is solved for estimations and not solved for actual values, though, it is acceptable at significant measurement noise levels of x_i, controlling actions U and their limits.

The mentioned property of solution of Eq. (1) for estimation of state coordinates and control implies strict requirements to accuracy of measurement accuracy of numerous state coordinates and control.

Common approach to solution of monitoring problem is reduced to vehicle equipping with numerous additional data sensors, necessity to use interface hardware, algorithms and software aiming at necessity to provide reliability and operation rate, which is accompanied by impairment of nearly all consumer specifications including expenses of purchasing and maintenance expenses.

Nontrivial solution of the problem presented in this work applies virtual data sensors based on mathematical models of the object and algorithms of indirect measurements. In this case the number of data sensors is reduced to minimum [11,12].

B. Algorithm

Control algorithms of traction, brakes, and path provide solution of the problem of stabilization of speed and distance to vehicle travelling in the same direction, automatic braking without wheel blocking, steady path control, and prevention of vehicle toll-over.

The problem solution is based on software core comprised of a set of virtual data sensors and control algorithms implemented in minimum hardware configuration.

Motion path of unmanned vehicle convoy is automatically plotted by manned master vehicle.

III. RESULTS AND DISCUSSION

Motion control system of unmanned vehicle convoy with manned master vehicle was tested in August, 2019 at Dmitrov test track (NAMI) which is a unique testing facility of road structures.

KamAZ-43118-0006010-D5 and KamAZ-43118-0006038-D5 dropside trucks were used as unmanned vehicles and KamAZ-43118-0006027-D5 crew bus truck was used as manned master vehicle. The vehicles were equipped with 9-speed robotized gearboxes, and 425/80R21 KAMA and TYREX tires, as well as with computer vision systems (radars, lidars, and video cams), satellite and wheel navigation systems, control units of traction, brakes, and steering. General view of unmanned KamAZ vehicles with manned master vehicle is illustrated in Fig. 1.

Fig. 1: General view of unmanned vehicle convoy with master manned vehicle

Mathematical models of vehicles were adjusted using truck scale of the test track (Fig. 2) where curb weight and axle load distribution were determined as well as wheelbase and axle track.

Fig. 2: KamAZ-43118 on truck scale of test track

The tested vehicles were equipped with instruments for measurements of longitudinal speed of mass center, covered path, location coordinates (Racelogic VBOX 3i), longitudinal and transversal accelerations, as well as angular rate of rotation around vertical axis (TANS CORRSYS-DATRON), and MSW measurement steering wheel to detect steering angle. Figure 3 illustrates positions of the instruments in unmanned KamAZ cab.

Fig. 3: Instruments in unmanned KamAZ cab

Motion control system of unmanned vehicle convoy with manned master vehicle was tested at dynamometric track and segment of specialized tracks of Dmitrov test site according to approved test program and procedure.

This article describes experimental results of monitoring system of motion variables, including longitudinal speed, covered path, longitudinal and transversal accelerations, turning angle of driven wheels with accounting for side slip angle, longitudinal slide of wheels, pressure in tires, as well as braking in front of fixed obstacle.

Figure 4 illustrates longitudinal speed of mass center V_m, longitudinal acceleration a_m and covered path L_t at the reference segment of dynamometric track as a function of time in acceleration mode with gear shifting to 17 m/s (61.2 km/h) with subsequent braking to standstill at the end of reference distance.

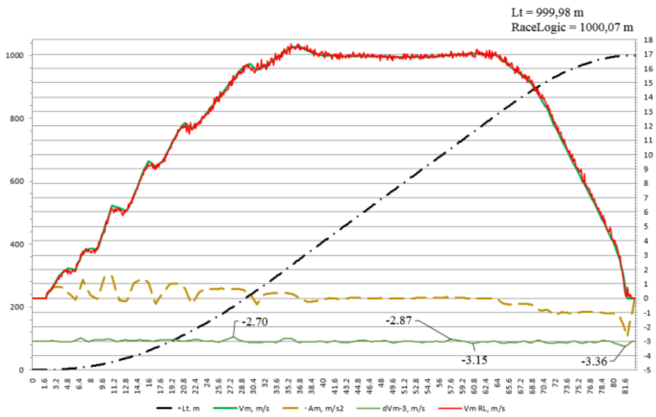

Fig. 4: Longitudinal speed of mass center V_m, longitudinal acceleration a_m and covered path L_t at the reference segment of dynamometric track as a function of time

A series of runs was carried out at the speeds of 10, 20, 30, 40, 50, 60, 80, and 100 km/h. The runs at the speeds higher than 60 km/h were carried out at 2-km segment of dynamometric track aiming at restriction of acceleration and braking. Analysis of measured longitudinal speed and covered path demonstrates that the measurement errors do not exceed 0.15 m/s and 1.0 m.

Measurements of turning angle of driven wheels with accounting for side slip angle and transversal acceleration were tested at specialized track circle with the radius of 25 m in the speed range from 10 to 40 km/h. Figure 5 illustrates turning angle of driven wheels DC, transversal acceleration Aq, and longitudinal speed of mass center Vm as a function of time as well as reference values of these variables detected by TANS CORRSYS-DATRON navigation sensors and MSW measurement steering wheel.

Turning angle of driven wheels DCW was detected by MSW measurement wheel with accounting for coefficient of reduction of steering unit. Actual values of turning angle of driven wheels DCM were determined by data of angular speed sensor with subsequent conversion by Euler equation for angular and linear speeds.

Transversal acceleration AqM was measured by TANS CORRSYS-DATRON navigation sensors.

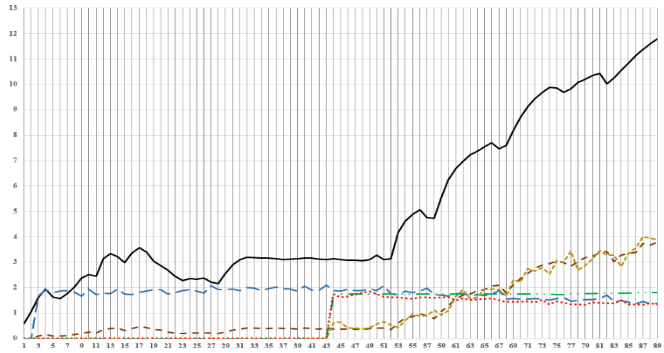

Fig. 5: Turning angle of driven wheels DC, transversal acceleration Aq and longitudinal speed of mass center Vm as a function of time

Measurement errors of turning angle do not exceed 0.01 rad, and errors of transversal acceleration are not higher than 0.1 m/s^2. It should be mentioned that indirect measurements of turning angle of driven wheels in the developed system were based on rpm of vehicle rear wheels.

Side slip angle in conventional variant is measured by three data sensors, in particular, sensor of steering angle, sensor of angular rate of rotation around vertical axis, and sensor of linear speed of mass center. In the developed system the slide slip angle of driven wheels is determined by wheel rpm, it does not require for any supplemental sensors.

Measurements of longitudinal acceleration Am and longitudinal wheel slides Sk were carried out at dynamometric track in acceleration and braking modes upon various decelerations up to activation of regular antilock brake system on dry bituminous concrete surface.

Automatic braking in front of fixed obstacle (Fig. 6) was tested using controllable EuroNCAP Vehicle Target (EVT).

Fig. 6: Unmanned KamAZ braking in front of EuroNCAP Vehicle Target

Figure 7 illustrates acceleration and braking of KamAZ from 11 m/s (39.6 km/h) as a function of time.

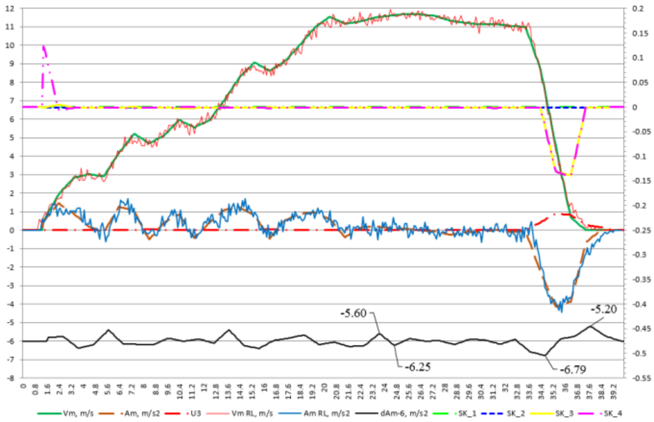

Fig. 7:Acceleration and braking of KamAZ from 11 m/s (39.6 km/h) as a function of time

The experimental results demonstrate that slide of front wheels upon start does not exceed 10% at acceleration of 1.7 m/s^2 equaling to -15% upon braking at 4 m/s^2, and estimation errors of longitudinal acceleration Am do not exceed 0.1 m/s^2 for established modes of variable accelerations.

Tire pressure control was also tested on dynamometric track. The tire pressure was preset by regular system of automated pumping up to 3 bar. The test runs included segment of direct motion with turning by 180° and motion in opposite direction at the speed of about 11÷12 m/s.

Several runs were performed with normal pressures differing from rated values by thermal constituents equaling to about 0.1÷0.2 bar. The thermal constituent and pressure deviations from rated values were determined by the system using software of virtual pressure sensor. Then the pressure was reduced in a wheel by 0.7 bar. In the next run the pressure was reduced simultaneously in two tires by 1.0 bar. In the fourth run the pressure on two wheels was set to 0.5 bar below the rated value, and in the third one – by 1.0 bar below the rated value.

Figure 8 illustrates pressure and its estimations in three of four controlled tires as a function of time.

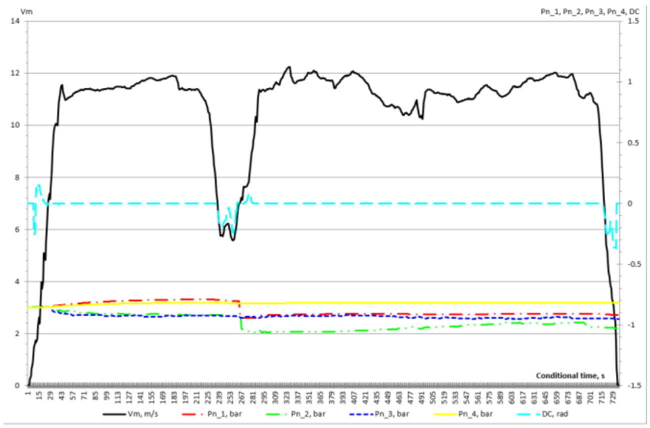

Fig. 8: Detection of pressure drop in three of four controlled tires as a function of time

The experimental results in Fig. 8 demonstrate that the established estimated pressures in wheels of one vehicle side (the front left and the rare left) are reached at about 2.6 bar with delay of 120 s, and the estimated pressure in the front right wheel reaches 2.1 bar with delay of ~240 s, which can be attributed to the properties of virtual pressure sensor in this situation, the most complicated for its operation. The errors of established estimated pressure do not exceed 0.1÷0.2 bar which corresponds to the accuracy of regular air gauges controlling pressure in tires.

Wheel navigation system integrated with satellite navigation system, radars, and video cams aiming at motion stabilization of unmanned vehicles along the path of manned master vehicle was tested at initial segment of dynamometric track. Input data of the wheel navigation system are wheel rotation frequencies and output data are state coordinates of vehicle mass center in Cartesian system with the origin in the starting point.

Figure 9 illustrates video record image with real time displaying in unit of processing and presentation of KamAZ motion about a closed path with the length of 410 m and common point of start and finish. The error of positioning does not exceed 2m, which is less than 0.5% of the covered path.

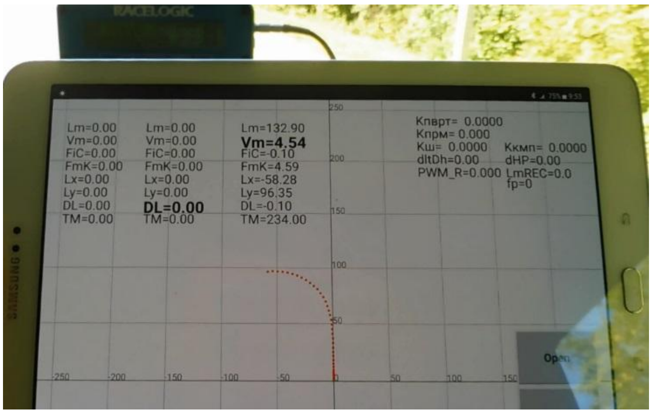

Fig. 9: Video record image with real time displaying in unit of processing and presentation of KamAZ motion about a closed path.

Recognition of road markings by data of wheel navigation system was carried out at 1 km segment of dynamometric track with 10 road markings installed each 100 m from one another.Figure 10 illustrates video record image from KamAZ cab. The data processing unit displays image of the nearest road marking.

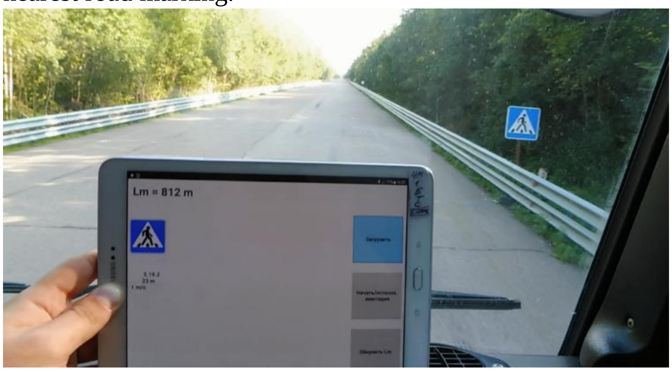

Fig. 10: Video record image from KamAZ cab with recognized crosswalk sign 5.19.2

It should be mentioned that reliability of recognition of road markings by the developed system does not depend on day time, illumination, precipitations, fog, spatial orientation of markings, their contamination or damages, which compares favorably with other systems based on image processing [13, 14, 15].

IV. SUMMARY

The obtained experimental results of motion control system of unmanned cargo vehicle convoy confirm both operability of the proposed engineering approaches to measurements to major motion variables and sufficiently high accuracy of indirect measurements in data segment of the system based on virtual data sensors.

Thus, the estimation errors of longitudinal speed of vehicle mass center in the range of working speeds do not exceed 0.15 m/s, which is unreachable for modern regular speedometers.

The estimation errors of longitudinal and transversal accelerations in the working range do not exceed 0.1 m/s^2, which is comparable with the errors of modern accelerometers.

The estimation errors of pressure drops do not exceed 0.1÷0.2 bar, which corresponds to the accuracy of wheel air gauges.

The estimation errors of turning angle of driven wheels with accounting for side slip angle do not exceed 0.01 rad, which is unreachable for modern steering sensors.

The solution errors of navigation problem by the wheel navigation system based on virtual data sensors do not exceed 1÷2 m, which is comparable with the errors of satellite navigation systems.

Reliability of recognition of road markings based on data of the wheel navigation system is also unreachable for image recognition systems.

It should be mentioned that the input data for solution of the considered monitoring problems of state variables are frequencies of wheel rotation measured by regular sensors of vehicle antilock system

V. CONCLUSION

The following conclusions can be made on the basis of the obtained results:

– solution of the problem of safe control of vehicle convoy is reduced to dynamic stabilization of state coordinates of vehicle convoy;

– solution of the problem of dynamic stabilization of state coordinates assumes the use of adequate estimations of state variables generated by data segment of motion control system;

– application of virtual sensors of vehicle motion variables allows to reduce significantly total number of physical sensors, to increase reliability, and to decrease total cost of the system and its maintenance;

– the experimental results confirm operability of virtual sensors of main vehicle motion variables;

– the use of high accurate estimations of motion variables for solution of control problems of unmanned vehicle convoy creates backgrounds for commercial development of innovative cargo vehicles with cardinally new specifications;

– the obtained experimental results make it possible to initiate development of new unmanned cargo vehicles which provide significant increase of cargo traffic.

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