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AUTONOMOUS COLLECTIVE ADJUSTMENT OF VEHICLES MOTION ON A HIGHWAY

G.G. Stetsyura[1] and O.V. Mosin[2]

[1]Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia
[2]JSC Rosoboronexport, Moscow, Russia

[1]✉ gstetsura@mail.ru, [2]✉ mosin.oleg@gmail.com

Abstract. This paper describes a fully autonomous decentralized method for synchronizing the interaction of vehicles moving on a highway. The method synchronizes the vehicles using simultaneous signal transmission from a group of transmitters to a group of receivers. With this feature, data exchange speed is increased, and the computing abilities of vehicles are connected into a moving computing cluster. The autonomous system operates without external controllers. Due to decentralization, the group of vehicles implements the synchronization process without any system control center. The group members interconnect via wireless optical and radio communication channels. There are two interacting stages of the synchronization process. The first stage is intended to perform decentralized coordination and information exchange within the group and determine the location, speed, and motion direction of the group members. The first stage passes initial information to the second stage. The second stage provides much more accurate vehicle tracking data and simultaneous information exchange between the groups of transmitters and receivers. Message transmission is synchronized very precisely (up to a single bit). In particular, necessary information about *n* vehicles is quickly acquired and transmitted to all receivers using one common message containing no more than *n* digits. Thus, the provided solution allows collecting the necessary information for vehicle coordination on highway sections, combining every vehicle's computing capability into one mobile computing cluster.

Keywords: autonomous vehicles, vehicle synchronization, decentralized object control, group interaction of mobile objects, fast in-network computing.

INTRODUCTION

Due to the rapid development of unmanned, highly automated vehicles, the need for automatic motion tracking and adjustment means has increased. Relevant research and development are mainly carried out within three approaches with numerous publications. Tracking means are developed using:

1) satellite navigation aids,
2) radars and lidars installed on the vehicle,
3) vision aids (see the surveys [1, 2]).

Solutions of the second and third approaches operate autonomously. They determine the distance to other vehicles within the line of sight with accuracy and speed sufficient for the object's safe motion. (From now on, we will use the word "object" instead of "car" and "vehicle" whenever possible.) However, these approaches do not determine the mutual location of all objects on a highway section. The solutions of the first approach determine the mutual location of all objects, but they are not autonomous and require interaction with satellites or special ground stations. The mutual location of moving objects is determined based on known coordinates, but accuracy is lower than in the second and third approaches. All approaches can be used jointly.

The methods proposed below for tracking and adjusting the motion of objects on a highway are autonomous, decentralized, and add new capabilities for the above three research approaches. Compared to the first approach, the dependence on signals from external sources is excluded; the accuracy of determining the location of objects is commensurate with those of the second and third approaches. For the second and third approaches, a new capability is that each object can now determine the current location of all objects on a highway section. A new feature also distinguishes the proposed methods from all approaches. Simple, computer-free communication facilities allow object computers to perform important distributed calculations for estimating the states of objects directly in the network. These operations are performed during data exchange between objects, causing no additional delays. Moreover, their duration does not depend on the number of objects participating in the operation. The new capabilities are divided into two groups as follows.

The first group performs motion adjustment, common for all objects on a given highway section. The objects act collectively, and each object simultaneously provides information about its state and actions to the entire group. These actions are executed with speed sufficient for tracking the motion of objects on a highway. Information about the group's current state allows making better private decisions and coordinating them. These tasks are performed by the synchronization process SP_0 proposed below.

The second group applies higher requirements to the interaction of objects. Each moving object has a control computer, and all objects interact via their computers. The group of objects should also be treated as a computer cluster operating in the hard real-time mode with the following features. Distances between cluster members are continuously changing while solving a current task. The composition of objects on a highway section (cluster members) changes in fractions of a second. The computers within a section have a history of their actions, which needs to be considered. The motion control task consists of small subtasks performed by cluster members in the hard real-time mode. The resources of such a cluster need to be shared with fast access to parts. For such a cluster, it is possible to perform the fast distributed collection of information about the state of n objects and deliver only one common message to all objects. This message combines same-name digits from the messages of n objects; see Section 5.

The group of computers acts as a single cluster, restricting the length of highway sections for their operation. Actions at hundreds of meters are significantly less flexible than those at tens of meters. This feature will be considered below. Thus, the second capability is that the objects act as a single mobile computer system.

The capabilities mentioned are achieved by introducing accurate synchronization of object actions. In this case, object coordinates are determined with an error not exceeding those of the above methods within the range of allowed transport speeds. Objects act synchronously and exchange information about the object location directly when determining the object coordinates. All active equipment can be installed directly on the object. Objects exchange data about their current location at high speed. Hence, their computer resources can be used as a common resource for solving a single motion safety task. All these tasks are solved based on the synchronization process SP.

The main purpose of this paper is to supplement the known solutions by acquiring timely data on the state of a distributed group of mobile objects and pooling the resources of computers controlling the movement of objects. Algorithms with such capabilities are not developed in the paper.

The system combining highway sections and the objects on them has a variable structure. The motion conditions on adjacent sections at different points may vary significantly over time.

The proposed solutions are based on the paper [3], where the interaction of mobile objects of a more general form was considered, and on the earlier paper [4]. However, they contain new capabilities considering the specifics of the above tasks.

The remainder of this paper is organized as follows. Sections 1–3 consider synchronization of object actions with accuracy sufficient to adjust the motion of objects based on their states. In Section 4, we propose a synchronization method under which the computers of objects operate as a single cluster. Section 5 presents distributed cluster operations executed at a rate independent of the number of their participants. In Section 6, the effect of the environment's state on the accuracy of the proposed synchronization processes is studied.

1. PARTICIPANTS OF MOTION ADJUSTMENT PROCESSES

Let us address the figure below.

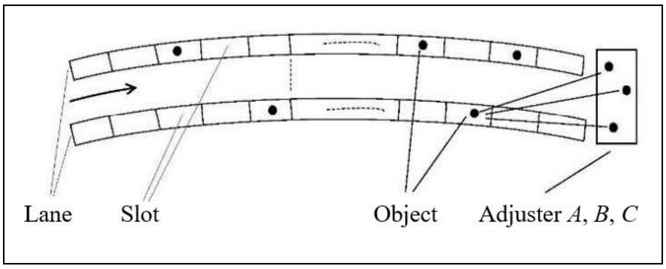

Fig. Highway section with motion adjustment.

The highway on which the objects move is divided into sections of a length L meters (possibly individual for each section). A group containing no more than n objects can be located within a section simultaneously; their speed and location vary over time. The highway has p lanes in one direction. The object's length is at least l meters. In front of each object, there should be a free section (interval) of a length d without other objects for safety purposes. (In what follows, $d = 2/3l$.) At the end of each section, there is a passive or active motion adjuster containing a source of signals. In the simplest case, we have a passive adjuster with at least three passive optical retroreflectors spaced sufficiently to perform trilateration with a required accuracy. They return the light signal coming to them from the moving object. Trilateration and an example of its application in robotics were described in the standard [5]. Each retroreflector is equipped with a light filter that passes a particular frequency band. We denote by A, B, and C the filters and their frequencies. The relative position of the retroreflectors in the adjuster is fixed.

Such passive equipment on the highway is sufficient to execute the synchronization process SP_0; see Sections 2 and 3. In the paper, additional complication of the equipment on the highway is introduced only when necessary. For example, an active repeater of optical signals in the adjuster is used in Section 4 to operate the objects in the mobile cluster mode (to execute the synchronization process SP, more accurate than SP_0). If an active adjuster is used, the objects will send both optical and radio signals to it. Also, we show the possibility of using an arbitrary mobile object as an adjuster and leaving only passive equipment on the highway.

The objects contain a computer that controls their motion, an optical pulse source that routes the object signals to a passive adjuster, and a receiver for the reflected signals, acting independently of the radio transceivers for the signals exchanged between the objects.

Each object is provided with a highway map in advance. The map captures static information about the current highway section, such as markings, warning signs, and the adjuster's coordinates and interaction features. The signal frequencies allowed for objects in the current highway section are included in this information to simplify interference control. The map also contains similar data for the next highway section in the motion direction.

The object's computer plots the following dynamic information on the map:

– the current coordinates of this object and all objects that have transmitted their coordinates;

– the object's permanent individual registration number;

– the location of the object body on the map (see subsection 2.2).

Each lane on the highway section map is divided into slots sl of the length $(l + d)$, where the parameters l and d are defined above. As a result, the map is covered by a grid of slots, and a vehicle can occupy one or more slots.

Each object transmits and receives radio signals on the frequencies allowed for the current section. In addition, it receives radio signals of the objects located on the next section.

With messaging rights, an object can transmit broadcast, group, or individual messages. (An individual message is addressed to particular objects.) New object coordinates received in the message simultaneously correct the maps for all objects.

2. DETERMINING THE LOCATION OF OBJECTS IN THE PROCESS SP_0

2.1 Distance to the motion adjuster: alternating determination by the objects

Each object interacting with the motion adjuster knows the highway section length L. Hence, each object also knows the signal interval T_1 within the section. For determining the distance, objects need to be assigned sequential numbers; they are described below. Objects wait for the absence of signals transmitted by them and the motion adjuster during the interval T_1 and transmit a special radio signal S of a duration not less than T_1. At the instant S^* of its completion, process 1 is executed: the next (first, second, etc.) object is allocated. Then this object determines its coordinates using process 2. Other objects wait for the completion of the first object; the next object sends its signals, and so on until all other objects on the section complete similar operations. The first object can determine its coordinates again only after all objects on the section have done so. During the process SP_0, the objects alternately determine their coordinates. However, they must not limit the speed allowed for highways.

Any object starts the next message transmission after all objects in the section have completed message transmission. Hence, the object may change its position significantly during this time, which is not considered by the process SP_0. This fact is the main restriction for the accuracy of the process SP_0. In Sections 3 and 4, we take some measures to reduce the mentioned pause.

In this section, only the passive motion adjuster is used. For the sequential numbering of objects, we first adopt the license plates of the cars. For example, over 50 million cars are registered in Russia. Representing their license plates as binary numbers requires $a = 26$ digits. This numbering option is the simplest but slowest one. In other sections, the numbering method will be accelerated.

Further, the adjuster measures the object's coordinates using the following information: the highway section length L; the number of lanes in the corresponding direction, p; the object's minimum length l; the object speed v; the maximum possible number of objects on the specified highway section, n; the speed of light c; the number of binary digits required to identify each object, $a = 26$.

We use the relations

$$T_1 = L/c,\ T_2 = (2a + 3)\ T_1,\ n = 3pL/5l,\ T_3 = nT_2, \quad (1)$$

where T_1 is the time required for the signal to pass through a section of the length L (particularly for the signal to reach the retroreflector from the farthest object). The time T_2 is determined by the time required to select the smallest number in the group of 2^a-digit numbers. We add two times to T_2: the time $2T_1$ to measure the distance to the retroreflector and the time T_1 to transmit data to other objects. A large amount of data can be transmitted in the time T_1. The formula for n gives the maximum number of objects located simultaneously on a highway section with p lanes. Here, the factor 5/3 at l considers the minimum distance d to the next object (2/3 of the car body length as recommended in the literature). After the time T_3, all objects on the section complete the distance measurements, and the objects start a new cycle of determining distances to the adjuster. If the number of objects is less than n, part of the interval T_3 will not be used. Suppose that the speed of objects on the highway is $v \leq 180$ km/h (50 m/s).

All objects on the section must start measuring times and distances with a minimum variation over time. To do this, they apply process 1.

Process 1 (identifying the object with the current smallest number)

Step 1. The object transmits radio signals with the highest bit of its sequential number (the most significant bit among the ones not transmitted in this process earlier), which contains a digits. The value "1" is transmitted by the frequency signal f_1; the value "0," by the frequency signal f_0.

Step 2. If the object that transmitted signal f_1 in Step 1 receives the signal f_0 from other objects, it stops executing process 1. The remaining objects proceed to Step 3.

Step 3. The object checks whether there are bits of the sequential number not transmitted in Step 1. If any, the object returns to Step 1; otherwise, process 1 is complete.

Remark to Step 1. The original version of this simple process is the decentralized priority Control (DPC) method: the object with the highest current priority gets the right to transmit the message. For the wire bus, this method was developed in 1970 at the Institute of Automation and Remote Control (now Trapeznikov Institute of Control Sciences) of the USSR Academy of Sciences [6]. DPC capabilities were extended in the monograph [7]. This method was applied in process control systems. Its wireless version was described in the paper [3].

Process 2, following process 1, defines the object's coordinates.

Process 2 (determining the object's coordinates).

Step 1. The source of the object's optical signals simultaneously sends signals in frequency bands A, B, and C to the retroreflectors A, B, and C for the adjuster. The retroreflectors A, B, and C return the signals to the objects. Each of these signals is received by the corresponding receiver at the object. Timers are associated with the source and receivers of the signals. When sending a signal, the source starts all timers simultaneously. When a reflected signal is received, the receiver stops the corresponding timer.

Remark to Step 1. With the simultaneous transmission of signals to the three retroreflectors A, B, and C, the process *SP* eliminates the influence of object motion on the accuracy of measurements when computers execute fast processes; see Section 5. In this case, the distances to the reflectors determined during the last distance measurement will slightly differ from the real ones.

Step 2. Given the signal velocity c and timer counts, the object's computer determines the distances to the retroreflectors; using trilateration, it calculates the object's coordinates relative to the adjuster position.

For the receivers to be unaffected by source signals, the timers start when the transmission is complete and stop when the reflected signals are received.

Step 3. The object transmits radio signals with its coordinates (and additional information if necessary) simultaneously to all objects. Using the special radio signal rs^*, the object informs the other objects about completing its measurement.

The object transmits its coordinates to other objects through radio signals in the extra time T_1. This transmission can be combined with measuring the distance of another object to the adjuster when sending optical signals to the latter.

Variant of Step 3. Sending the signals A, B, and C, the object transmits a radio signal to all objects about sending the signal. When each of them returns, the object sends appropriate radio signals to other objects. Based on the received data, the latter objects calculate the coordinates of the object that sent the signals.

Remark to process 2. At any instant, this process involves a single signal source and a single adjuster that transmit a single signal. Therefore, the adjuster's useful signal arrives at the receivers before its external reflections and does not affect the measurement. In Step 3, the receiver receives a message with binary zeros and ones sent by different frequencies.

First of all, we make sure that the ordering of objects' actions does not limit the motion speed on the highway. Also, the arrival of new objects on the highway section with lower sequential numbers compared to the existing ones must not prohibit the latter from determining their coordinates. Let us show that these conditions are satisfied.

First, we discuss the sequential ordering of object actions. Let the event S^* (the disappearance of the signal S) occur on some highway section. In this case, nearby objects will start transmitting the highest bit of their sequential number. In the time T_1, these signals will leave the section. In the time T_1 after the event S, the most distant objects from this event will send their signals with their highest bits. After the time T_1, these signals will also leave the section, and the next bit of the sequential number can be transmitted, and so on.

Each section contains at most $n = 3pL/5l$ objects simultaneously. According to the relations (1), measuring their coordinates will require T_3 seconds, where

$$T_3 = nT_2 = n(2a + 3)T_1 = 3\,p(2a + 3)L^2/5lc. \qquad (2)$$

Given the speed v, in the time T_3 the object will move to the distance $\Delta S = vT_3$ meters. For the parameter values $L = 50$ m, $l = 2$ m, $p = 10$, $a = 26$, and $v = 50$ m/s, we have $\Delta S = 7.125$ cm. As a result, the location of the objects on the maps will not change: the objects will be shifted by less than 3% of the slot length.

Similarly, when a new object enters a highway section with a speed v, measurements for all objects will be completed before the new object occupies one of the section slots.

The obtained result is acceptable for the measurement of coordinates. Moreover, it can be improved by excluding the dependence on the number a (changing the sequential numbering of objects). This issue will be considered in Section 3.

2.2 Motion rules for objects on a route section and when entering a new section

Let us return to the map defined in Section 1.1. The standard slot-to-slot motion of an object is within the lane it occupies. There must be a free section of the lane with a length of at least $(l + d)$ meters in front of the object. The standard motion does not need to be coordinated with other objects. Moving to another lane requires coordination with an object in this lane. The details of their interaction are a matter of particular implementation. However, the actions outlined above allow an object to send its request and repeatedly exchange motion details.

Two consecutive measurements (or two simultaneous measurements taken from different locations on an object's body) determine its orientation and position on the lane. The object transmits these data to other objects.

Thus, within the interaction described in Section 2, objects timely inform their neighbors on the highway section about their position on the highway on time, but motion control is not considered.

The object has a map of the next highway section. Hence, transition to the next section means changing the signal frequencies and using the new section map.

3. ACCELERATING THE PROCESS SP_0

Here, the measurement accuracy of object's coordinates is improved by eliminating the dependence of the exponential a on the number of vehicle license plates. This approach reduces the time between successive measurements of the distance to the motion adjuster.

The measurement order is dictated by the map, more precisely by the current highway section divided into the n numbered slots (see above). The measurement process starts in the same way as before. However, after the signal S signal finishes, all section *slots* get the right to perform the measurement one by one. If an object occupies several slots, it confirms the occupation of each such slot. If there is no object in the slot, the time allocated to the slot remains unoccupied. Since all objects have the same maps, the measurement process is accelerated if necessary by considering only the slots occupied by objects. An object on the map is also marked with an individual vehicle number.

As a result, we obtain the relations $T_1 = L/c$, $T_2 = 3T_1$, $n = 3pL/5l$, and $T_3 = 3nL/c$. Now in the time T_3, the object will move by $\Delta S = 3vnL/c$ meters. For the example from subsection 2.1, $\Delta S = 0.375$ cm. The environment's state can affect the accuracy of the measurement; see Section 6.

Slots allow using several adjusters on a highway section. For a slot or a group of slots, an appropriate adjuster with the clearest signal will be allocated. Different adjusters will respond to different sets the frequency bands A, B, and C. The object map will indicate which object should be used for a particular slot.

On the ordered access of new objects to a highway section. The sequential process of determining the position of objects on the highway section has been presented above. Now we consider the ordered access of objects to a new section.

Let an access zone be a subsection at the end of a highway section immediately before a motion adjuster. The access zone length L^* is the slot length, i.e., $1.67l$

meters. It can contain at most $n^* = p$ objects, one object in each lane. The objects in the access zone are separated from the nearest adjuster by the distance L^*. Small values of L^* significantly accelerate determining the coordinates of the objects entering the next section.

We attribute an access zone to the current and the next highway sections simultaneously. Before entering an access zone, an object performs measurements using the nearest adjuster of the current section. An object in the access zone gets the right to enter the first slot of the next section, entering it similarly to the actions of all objects of this section to move to the next slot. That is, the number of section slots is increased by the number of access zone slots.

Objects may use sequential numbers or slot numbers on the object maps to enter an access zone. Then they apply processes 1 and 2. As a result, they receive entry numbers on the next slot starting with one; see subsection 2.1. Their subsequent motion will be tracked using the methods of Section 2 or 3.

The necessity to order object actions also arises when entering the highway from the outside. Thus, we have determined the coordinates of objects using license plates or maps available to the objects.

4. ORGANIZATION OF THE PROCESS *SP*

In the process *SP*, synchronization is accelerated by making the time T_3 independent of the number n of objects. As a result, the time required in the process SP_0 to measure the signal transfer time to the repeater for one object becomes enough to determine such times for all objects. During this time, all objects move to a smaller distance. The synchronization accuracy accelerates the objects control process in the mobile computer cluster mode. Another necessary condition for this mode is satisfied. In the distributed system, the messages of a group of source objects must be synchronized to arrive at a group of receivers in a given order (for example, simultaneously). The way to do this is to replace the source group with a single source, which forwards the source group messages to receivers without delay. As such a source, here we use a unified repeater and signal processor [4]. Then, the sources located at different distances from the repeater consider this difference, delaying the transfer of messages to the repeater. Upon receiving the messages of objects synchronized via delays, the repeater sends them without delay to all objects simultaneously. Synchronization is achieved. There may be several repeaters. In this case, the general task of motion control can be divided into interacting but asynchronously executed subtasks. Let us describe the process *SP* in detail.

Suppose that a repeater is a stationary active motion adjuster containing signal receivers and sources. We denote it by *CR*. Also, assume that the process SP_0 was executed: the objects determined the distance to the adjuster, and a separate communication channel, different from the one occupied by the process SP_0, was allocated for the actions of the process *SP*.

In addition, each object has the current distances between all objects and the adjuster on its electronic map. Suppose that the process SP_0 was executed, and the signal transmission times from the objects to the adjuster *CR* are known.

We introduce the concept of a logical scale as a bit sequence *LS* where each bit is allocated to a separate map slot.

In the synchronization process *SP*, the scale *LS* is sent using all objects on the section, e.g., in the following way. The objects send to the adjuster *CR* the signal *S* discussed above; the adjuster *CR* returns it to the objects at another frequency in the form of a new signal *Scr*. The object detecting Scr^* (the instant of completing the signal *Scr*) sends a delayed pulse signal s to arrive at the adjuster *CR* in the middle of its logical scale bit. Free space is left in the bit on both sides of the signal s.

An object sends a signal to the adjuster *CR* with the delay $D = T_1 - T_i$. Here T_1 is the signal transfer time within the highway section, and T_i is the signal transfer time between object i and the adjuster *CR*. With such a delay, the same-named bits of the scales of all objects will arrive at the adjuster *CR* at the specified instants, forming a common scale.

CR retransmits the scale *LS* to all objects in a similar scale LS^* in which the signals s are replaced by the signals s^* of a different frequency. Due to the motion of objects, the bit position of signal s^* shifts, and the object corrects the distance to the adjuster *CR*.

Let us estimate the influence of motion on the accuracy of time measurements by objects. The time Δt occupied by a scale bit completely depends on the speed of objects. The motion of objects must not lead to the transfer of the signal s^* from the bit belonging to a particular object to the neighbor bit belonging to another object. When sending the signal to the adjuster *CR* and receiving the response signal s^*, the object can move by $\Delta s = 2vL/c$ meters. Due to the distance change, the signal s^* in the scale will shift by the time $\Delta t = 2vL/c^2$ seconds, and the duration of the scale bit must not be less than this value. For the values L and c in the examples above, we have $\Delta t = 0.056$ ps. Thus, scale transmission can be performed at very high speeds. All n bits of the scale will be transmitted in 8.4 ps; the scale can be transmitted even 396 times while an object exchanges a single pair of s/s^* with the adjuster *CR*. The dependence of the distance measurement time on the number *n* of objects is preserved but decreased many times, becoming insignificant for the process *SP*.

Up to this point, we have adopted the active stationary motion adjuster *CR* in the process *SP*. Let us combine the passive stationary adjuster with the mobile one (*mCR*). Assume that an object was allocated to act as *mCR* before the process *SP* starts. The object *mCR* determines its current coordinates by measuring the distance to the adjuster *CR*. The coordinates of *mCR* become known to all objects. Then they perform the *SP* actions by exchanging signals with it instead of the stationary adjuster.

This section completes the presentation of synchronization methods for the interaction of objects on a highway. The following sections will discuss the application of the process *SP* and the effect of external interference on the processes SP_0 and *SP*.

Concluding the description of synchronization processes, we note two well-known approaches to develop technical means for implementing the processes considered in Sections 1–4.

A more complex version of synchronization than estimating an individual signal shift can be performed by sending special synchronization messages. For example, very accurate stationary measurements were implemented in the White Rabbit project for physics experiments at CERN [8–10]. Here, the nonius range measurement method was applied, replacing a separate signal with a more complex message. For fiber-optic communication lines, the synchronization accuracy of message transmission over the line is better than 100 ps over a distance of more than 16 km when the temperature varies within the range 12.5–85.0ºC. Special synchronization correction devices are built into the network hardware.

Active optical phased arrays with high-speed beam travel [11] are gradually replacing mechanized object detection. With such an approach, the object determines the position of the adjuster quickly, uses the energy of the object signals more efficiently, and reduces the interference caused by the reflection of the object signal from external objects.

5. APPLICATION OF THE PROCESS *SP* BY OBJECTS

The solutions outlined in this section are important for managing the behavior of mobile objects equipped with increasingly powerful computers. As a result, an object can solve increasingly complex control tasks considering the current behavior of all objects. However, the objects are connected through a very loaded resource (shared communication channel). Methods are required for objects to execute distributed computational and control operations with low channel load. Such methods will accelerate the operations; see their description below.

This section does not discriminate between the adjusters *CR* and *mCR*. Therefore, we introduce the generalized abbreviation *aCR* (*active CR*) for them.

5.1 Management of synchronous messaging by objects

Assume that an object sends a command via the adjuster *aCR* to all objects: permits the synchronous transmission of their messages. Upon receiving the command, the objects willing to transmit a message respond by sending a logical scale to the adjuster *aCR*, placing "1" in their digit of the scale (the signal f_1). The scales of all objects should come to the adjuster *aCR* with combining the same-name bits. For this purpose, each object O_i sends its scale with the delay $D_i = L_{\max} - L_i$, where L_i is its distance to the adjuster *aCR*, and $L_{\max}$ denotes the highway length. The resulting scale comes to the adjuster *aCR*, and it sends it without delay to all objects, replacing the signals f_1 with the signals f_1^*. Upon receiving all scale bits from the adjuster *aCR*, each object O_i sends its message to the adjuster *aCR* with the delay D_i. The adjuster *aCR* uses radio signals to send the received total message to all objects. Objects may need to transmit messages one after another. In this case, it suffices to transmit them considering the messages transmitted by the preceding objects. Therefore, we have a time gain: the objects' messages are transmitted as a single message at a rate depending only on the selected transmission frequency (and not on the distance between the objects and the adjuster *aCR*).

For the distributed computations shown below, the objects' messages must be transmitted with the simultaneous arrival of the same-name bits to the adjuster *aCR*.

5.2 Eliminating access conflicts to the adjuster *aCR*

In subsection 5.1, the objects are synchronized by a command of one object. However, self-synchronization of message sources is also necessary. Assume that the objects determined the distance to the adjuster *aCR*. Suppose that there are currently no signals, and the objects can start message transmission without a special command. Then the objects start transmitting messages to the adjuster *aCR* and receive the transmission result from it. If a conflict occurs, then at least one bit of the message will simultaneously have the signals f_1* and f_0* created in the adjuster *aCR* from the signals f_1 ("1") and f_0 ("0") sent by the objects. The appearance of these signals is perceived as a synchronization start command, and the synchronization process described in subsection 5.1 is executed. The access conflict is therefore eliminated.

5.3 Simultaneous data acquisition on the state of all objects

The paper [4] considered distributed computational processes in which computations are performed directly in message transmission without delay. Their applicability to motion-tracking tasks requires a more detailed study of the needs in particular situations. Therefore, we will present only general (typical) examples.

Estimating the state of all parameters for all objects (bitwise logical AND and OR operations). Let the state of each object be described by the same set of quantitative parameters. (For example, a group of parameters estimating the conditions of the vehicle engine, brakes, stability, etc.) Objects transmit all parameters in the form of a logical scale: a binary sequence in which each parameter has a separate bit. If a parameter value meets the specified requirements, the object bit is assigned "1" by transmitting the frequency signal f_1. Otherwise, "0" is transmitted by the signal f_0. Objects transmit scales when they receive a corresponding command through the adjuster in the process *SP*. As a result, all scales of the objects arrive at the adjuster with combining the same-named bits. All objects receive the combined scale. If the command was to perform bitwise logical AND over the scales, then the presence of the signals f_1 and f_0 (or f_0 only) in the combined scale bit is considered "0"; otherwise, "1." If the command was to perform bitwise logical OR over the scales, then the presence of the signals f_1 and f_0 (or f_1 only) in the combined scale bit is considered "1"; otherwise, "0." Thus, the simple synchronous retranslation of scales performs without delay the specified calculations in a time independent of the number of participating objects.

Finding the maximum (minimum). Each object has measured values of all parameters mentioned above. For all objects, it is required to find the maximum (minimum) value of each parameter.

For this purpose, objects send a sequence of message groups simultaneously. The first group arrives at the adjuster *aCR* as a single message combining the same-name bits. Such a message transmits the highest digit of the first parameter. We represent this digit as a binary scale with the number of digits equal to the base of the numerical system selected for the parameter values. Only one bit of the scale corresponding to the digit value equals "1"; the rest are "0." For example, the scale for decimal digit 6 is 000100000. The following actions are performed to find the maximum (minimum) value of each parameter.

To find the maximum, the objects receive the digit from the adjuster *aCR* and check whether they sent the highest value of the highest digit or not. The objects that did not send the highest value will not participate in the check for the parameter. The others send a similar group of messages, but for the next digit of the parameter value. The process continues until all digits of all parameters are completed checked. As a result, the objects with the maximum value of each parameter will be identified. The minimum is found by analogy.

Note that the maximum (minimum) is determined using the same logic as the minimum sequential number in process 1; see subsection 2.1. However, this operation is significantly accelerated due to a special representation of digits (reducing the number of data exchange operations) and the process *SP*.

Analog-to-digital summation. For estimating the state of the entire system of objects, it is desirable to sum up the group of numbers sent by the objects directly in the adjuster *aCR*. Such operations were described in the paper [4]. They are organized as follows. An analog-to-digital converter (ADC) is added to the adjuster *aCR*. The digits of all summands are represented by scales, like finding the maximum (minimum).

Let us illustrate this operation on an example of summing up decimal digits simultaneously sent by a group of objects to the adjuster *aCR*. Let the 001(4)01(6)0001(7) scale be formed by superposing several digits (scales). The energy level of the signal coming to the ADC is given in parentheses for digits "7," "5," and "1," respectively. In this case, the adjuster *aCR* distributes the following result to all objects: four "7"s, six "5"s, and seven "1"s are transmitted. Each object independently collects the sum: $4 \times 7 + 6 \times 5 + 7 = 65$. For multi-digit numbers, all digits are similarly processed, and a total sum is formed. For subtraction, two sums are formed, and subtraction is performed.

Histograms estimating the state of numerous system parameters are created based on such operations. ADC operations require stable sources of optical signals. Such sources do exist. The paper [12] presented a simple LED source with output power variation below 50 ppm/ºC. The indicated operations were also performed in a time independent of the number of participants.

These operations are examples of an associative operation in which all objects participate simultaneously. The operation results are simultaneously supplied to all objects, allowing them to perform further actions considering the received data about the system state.

The examples in this section show that the objects operate as a single mobile computer cluster. It can be partitioned into small and asynchronously interacting clusters by applying the solution [13] (with an appropriate modification considering the specifics of mobile systems).

6. THE INFLUENCE OF ENVIRONMENT ON THE PROCESSES SP_0 AND SP

Changes in the environment's state, e.g., temporary deterioration of the quality of transmitted signals or the appearance of interference, affect the execution of the processes SP_0 and SP. The solutions considered in this paper are based on the results experimentally validated and applied in several fields. Therefore, to assess the implementability of the proposed approach, we address relevant publications.

The implementability of the passive adjuster. Road signs on highways reflect the vehicle signal and are clearly identified in the dark among reflections from other objects. The explanation is that road signs contain many retroreflectors. This use of retroreflectors is thoroughly studied and defined by technical requirements and standards. A passive adjuster is only required to be clearly distinguished by reflection from interference reflections. Hence, its application does not differ from the above, and it can be implemented as well.

The implementability of the active adjuster. This task is simpler. The signals coming into the adjuster and the signals returned by it are qualitatively different. Interference from them travels a longer path, lags behind the useful signal, and does not interfere with measuring the object's distance to the adjuster.

Message transmission by the active adjuster using the process *SP*. The papers [14, 15] demonstrated an interaction scheme of the optical message source and receiver as follows. The receiver sends a continuous optical signal, which is received by the retroreflector of the message source and returned by it to the receiver. There is a signal modulator on the path of the returned signal, which translates the returned continuous signal into a message. The system's operability was tested in harsh conditions: 7 km-distance between the source and receiver, sea environment, fog, and heaving. The data transfer rate was 40 Mbit/s. Here the message transmission structure is similar to that of the active adjuster. However, the latter device is in better conditions using its signal source. This example shows the implementability of message transmission on a highway section.

We give another example. In the paper [16], a source of optical non-directional digital signals at short distances (a few meters) was considered, and a transfer rate of 400 Gb/s was obtained for it. The communication structure presented therein is as follows. There is a non-directional LED source in a room, modulated by electrical signals with a frequency of 400 Gb/s. The source sends a message to a group of receivers connected to the final recipients (computers). Delayed reflections from external objects do not violate the operation of this system. Such a source is also close to the active adjuster.

Thus, we have provided examples of optical communication useful for creating active optical adjusters. Radio means are more widespread and therefore not considered here.

Interference from signals generated in neighbor highway sections. Usually, such interference is eliminated by distributing frequencies of transmitted signals: neighbors use different frequencies. As applied to highways, this approach is implemented in the following way. The k neighbor sections of the highway use different frequencies of optical and radio signals. Then the order is repeated, and each highway section will be separated from the interfering (k – 1) sections. The object gets information about the chosen frequencies from its electronic map or by polling the passive adjusters. In this case, the adjuster's passive retroreflector must have additional light filters. For example, a combination of three light filters opened in different combinations corresponds to k = 7.

Individual correction of object signal level. Like measuring the object's distance to the adjuster, we can control the level of the object signal coming to the adjuster. With the passive adjuster, the object performs this measurement, estimating the level of the signal returned to it. Assume that the conditions for the passage of the forward and reverse signals are the same. The active adjuster sends its signal measured by the object. Alternatively, the adjuster contains an ADC to estimate the level of the signal entering the adjuster. This method corrects the influence of the environment on the system operation.

CONCLUSIONS

The autonomous collective motion adjustment methods for vehicles on a highway proposed in this paper provide new capabilities. Let us emphasize them.

The methods complement the three most commonly used approaches: radar and lidar, vision aids, and satellite navigation aids installed on the vehicle (object). The first and second approaches are proximity methods estimating the mutual location of objects only within the line of sight. However, they measure the distance with high accuracy. The third approach determines the location of vehicles on a large highway section without requiring the direct line of sight. Unfortunately, it has lower accuracy than the previous ones and is not autonomous (depends on external navigation aids). The solutions proposed in this paper autonomously determine the location of objects on a highway beyond the line of sight and have an accuracy characteristic of the first two approaches.

Moreover, the proposed methods have another capability distinguishing them from the three approaches. With simple, computer-free means of communication, objects' computers perform several *distributed* calculations (important for objects' state estimation) directly in the network. These operations are executed during the data exchange between objects, causing no additional delays. Their duration does not depend on the number of objects participating in the operation. The precise synchronization of joint operations allows combining the same-name bits of messages for a group of objects. As a result, a group of messages is replaced by a single message without increasing the number of bits.

Hopefully, the proposed solutions will be useful in the ever-expanding market of fully autonomous vehicles, complementing the known results.

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Author information

Stetsyura, Gennady Georgievich. Dr. Sci. (Eng.), Chief Researcher, Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia
✉ gstetsura@mail.ru

Mosin, Oleg Viktorovich. Chief Expert, Security Department, JSC Rosoboronexport, Moscow, Russia
✉ mosin.oleg@gmail.com

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Translated into English by *Alexander Yu. Mazurov*, Cand. Sci. (Phys.-Math.), Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia
✉ alexander.mazurov08@gmail.com