Intersection management tasks in mobile robotic system with decentralized control

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Abstract. Busy urban traffic brings more and more problems for residents of large cities. The crossroads of two or more carriageways in the city are one of the main problems of traffic jams and delays on the road. The introduction of unmanned vehicles and systems capable of driving them safely and effectively can contribute to solving this problem. The authors propose to consider the problem of intersections in the context of a mobile robotic system, since the organization of a group of mobile autonomous robotic devices most closely approaches the organization of the movement of unmanned vehicles. The authors considered the main strategies for organizing a group of unmanned vehicles, proposed and described a model of the system that controls the traffic at the intersection. To assess the feasibility of the developed model, a software simulator was developed, which allows to compare the efficiency of the developed model with the traffic management system using traffic lights. The results of the experiments performed allow us to say that the model proposed by the authors makes it possible to increase the capacity of the intersection within the framework of this study.

Keywords: Intersection management · Intelligent transportation systems · Unmanned vehicle · Traffic control.

1 Introduction

The development of the intelligent transport infrastructure (ITI) is one of the most important areas of the internet of things (IoT). Automobile traffic in modern large cities is a source of emission of harmful substances into the environment, traffic jams and urban noise. In 2008, a study was conducted [6], which showed that traffic jams can arise from nowhere, due to a phenomenon called the traffic wave. It occurs due to the braking of one of the drivers, which leads to the braking of the rest. Moreover, the continuous growth of urban traffic leads to negative social consequences, such as increased mortality on the roads.

One of the ways to combat the increasing harmful effects that car traffic has on the environment is to introduce unmanned vehicles (UVs) and systems that can organize their movement efficiently and safely. Driverless cars combine different technologies, devices, detectors and sensors for interaction with the environment and to obtain information from it, such as radar, computer vision, lidar, navigation technologies, odometry, etc. Traffic control systems receive information from these devices and make route planning taking into account obstacles, other road users and road terrain features.

Many companies are successfully engaged in the development and design of UVs. For example, Waymo company [11] reports that on the 18th of October 2018, its driverless cars had successfully covered a distance of more than 10 million miles.

Obviously, the use of todays methods of managing road traffic in cities, such as traffic lights, will be inappropriate in the context of the ITI of a smart city using autonomous UV groups. Applying a multi-agent approach, one can imagine a multitude of cars as a multitude of agents interacting with each other and moving according to certain rules. The speed of reaction and the calculations of the systems that control UVs, require a rethinking of the existing traffic rules developed for vehicles operated by humans.

To solve the problem of intersection management, the authors of this paper proposed a model of the system for safe and conflict-free travel of intersections by UVs. The model assumes that there is a transport infrastructure object (TIO) at each of the city intersections, which is responsible for organizing traffic at this intersection. At the same time, all such objects of transport infrastructure are able to exchange data with each other and optimize movement in such a way as to reduce the total time spent on overcoming the intersection by all UVs of the system. To determine the feasibility of using the presented model, the authors developed a software simulator and made a comparison with the intersection controlled by a traffic lights. This paper is organized as follows. Section 2 reviewed the scientific literature in the field of research into the problem of intersection management and the organization of the movement of UVs. Section 3 provides a classification of strategies for organizing UV group control. Section 4 describes the proposed model for the functioning of a traffic control system at an intersection and describes the main criteria for its functioning. The results of the experiments using the developed software simulator and their comparison with the intersection, the movement of which is organized using traffic lights are given in section 5. Section 6 presents the main conclusions of the study and describes plans for further research.

2 Literature Review

The idea of traffic control is being developed using the ant swarm system [12] to solve the problem of managing a large number of vehicles and lanes. Research shows that the algorithm is reliable and efficient, experiments were conducted based on various scenarios for changing traffic. The original idea of the method is that a number of ants work together to find a solution to the problem by exchanging information encoded in pheromones. In the implementation of the system, the initial pheromone is the value of a certain parameter, on which the state transition rule depends when moving from one transport node to another, in the decision-making process, the pheromones are changed using local and global rules. As criteria, the following parameters were used to assess the system's efficiency: the time required to overcome the route by all vehicles, the throughput of intersections, the average delay of the vehicle, the average queue length of the vehicle during a conflict at the intersection.

The article [2] discusses the auction method (with paying the cost of travel at the intersection from ones own budget) as an approach to determining the procedure for overcoming intersections with vehicles, in such conditions vehicles can quickly make decisions on behalf of passengers. The paper discusses the use of auctions, stoplights and backup protocols, the creation of optimal routes for agents with minimal travel time. The implementation of the mechanisms takes place in the simulator, including the maps of the scale of the city. The authors hypothesize that in the real market agents will try to develop a budget saving strategy. At the same time, only fair wallet strategy will be the most profitable: if agents follow it, then they pay less compared to the initial rate.

Researchers propose an alternative mechanism for coordinating the movement of autonomous vehicles when overcoming intersections, based on the method of representing vehicles as autonomous agents in a multi-agent system. [4] The coordination method is based on a redundancy method built around a detailed communication protocol. The developed approach can significantly exceed the management of the flows of moving vehicle using traffic lights and stop signs. The capacity of the intersections is trivially limited from above by the capacity of the road, because traffic lights have low efficiency. The basic idea of the method is that the driver agents send a request to the infrastructure agents and try to reserve a space-time block at the intersection. The infrastructure agent decides to grant or reject the request in accordance with the intersection of the control policy.

In [8], the authors described an approach to the organization of a traffic control system at the intersection, which allows to significantly reduce the time spent by vehicles on crossing an intersection compared to traffic lights. This approach implies the organization of vehicles into a group called platoon and managed by one of the vehicles that is the leader vehicle agent (LVA). The system also assumes the presence of an intersection agent (IA) at each intersection, which implements motion control and reservation of time-space blocks on the intersection. Due to the fact that IA communicates only with LVA, the load on the communication channel is reduced by 90% compared with the case of [7], when IA needs to communicate with all of vehicles simultaneously, as was shown through experiments. The paper compares the results of three approaches to the organization of traffic control at the intersection: by means of a traffic lights, without organizing LVA group control, and by means of LVA. To increase the efficiency of the system and reduce the emission of harmful substances into the environment, the platoon-based approach is slightly worse than the non-platoon based approach, however, it can significantly reduce the communication load.

Au and Stone in [1] describe the developed algorithm for optimizing the intersection of vehicles. The authors refer to Little's law [10], on the basis of which they conclude that in order to increase the capacity of the intersection, it is necessary to reduce the average time spent by vehicle to overcome this intersection, that is, vehicles need to overcome the intersection at the maximum possible speed. Next, the work describes algorithms and criteria that optimize the movement of vehicles in order to pass the intersection at maximum speed, called by the authors acceleration schedule. The authors distinguish two problems: optimization and validation problem. Optimization problem is a search among a multitude of control signals of such a sequence that will allow vehicle to arrive at the intersection in less time and at the maximum possible speed. The validation problem is determining whether a vehicle can, following the acceleration schedule, arrive at the intersection without violating the established speed and time limits. The results of the simulation of the organization of the movement based on the developed criteria allow us to say that the average delay during the passage of the intersection is significantly reduced when the intersection is very busy compared to the control system presented in [5].

A good overview of current research in the field of intersection management is given in [3]. The authors examine in detail the methods and basic principles of modeling traffic at intersections, compare the results of the effectiveness of various methods and their effect on capacity, consider regulated and unregulated intersections, and also study the possibility of taking into account pedestrians and real drivers in the system.

On a flat road, UVs can move autonomously and safely. Existing technologies allow UVs to safely travel within the boundaries of the lane, change lanes and avoid obstacles. With intersections, everything is much more complicated - vehicles need to cross several trajectories of other vehicles at once, which can cause collisions in route planning systems for UVs. With the use of technical means available to UVs and allowing communication between road users, it is possible to implement a safe and effective system for controlling the passage of intersections. Applying a multi-agent approach, one can imagine a multitude of cars as a multitude of agents interacting with each other and moving according to certain rules. [4]

The speed of reaction and the calculations of the systems that control UVs, require a rethinking of the existing traffic rules developed for vehicles operated by humans.

3 Strategies for Managing a Group of Unmanned Vehicles

In this paper, the authors consider a group of mobile UVs as a mobile robotic system. Group management strategies are classified as centralized and decentralized (see Fig. 1). [9]

The centralized management strategy can be divided into two classes - strategy using the principle of unified management and a strategy using the principle of hierarchical management. In the first case, the group of objects contains a central control unit (CCU), which has a powerful computing center and carries out route planning, control and management of the activities of all the group

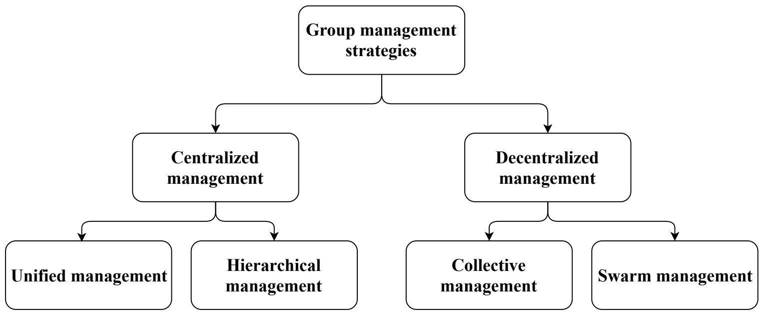
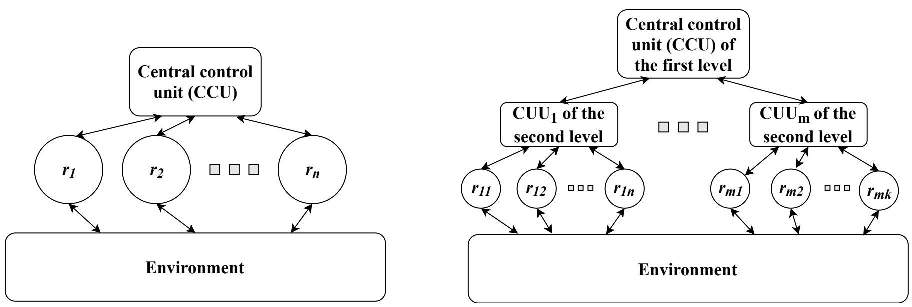


Fig. 1: Group management strategies.



(a) (b)

Fig. 2: Centralized group management strategies: (a) centralized unified management strategy, $r_1, r_2, \ldots, r_n$ - system elements subordinate to the central control unit; (b) centralized hierarchical management strategy, $r_{11}, r_{12}, \ldots, r_{1n};\ r_{m1}, r_{m2}, \ldots, r_{mk}$ - groups of elements subordinate to the central nodes of the second level.

objects. The objects of the group receive information from the environment with the help of sensors and detectors, transmit it to the CCU which, in turn, processes them and transmits various commands to the objects through which the group seeks to achieve a common goal. Diagram of the flows of information between the elements of the system is shown in Fig. 2(a). The advantages of such a system include the simplicity of its organization and algorithmization: only one central element is responsible for the formation of management tasks and their distribution. However, this strategy has a number of significant drawbacks. The CCU must have a powerful computing center, since it is entrusted with the task of optimizing the actions of all elements of the system. As the number of group members increases, the complexity of the optimization problem increases exponentially depending on their number, which may result in delays in making

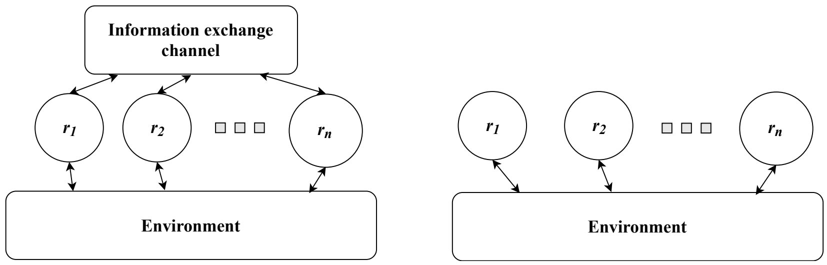


Fig. 3: Decentralized group management strategies: (a) decentralized collective management strategy, $r_1, r_2, \ldots, r_n$ - elements of the system that communicate with each other to achieve the goal; (b) decentralized swarm management strategy, $r_1, r_2, \ldots, r_n$ - elements of the system.

decisions that may be unacceptable when using systems with a similar strategy in the organization of transport infrastructure.

When using a hierarchical control strategy, there are several levels of control elements in the system. The first level CCU controls a certain number of subordinates of the second level CCU, each of which is in charge of a group of robots. In such a scheme, second-level CCU receive information from agents subordinate to them, process it and transmit to CUU of the first level, which, in turn, processes it and forms tasks that are transferred back to the second level and distributed among agents of each group. The advantage of such a scheme is that, compared with the unified management strategy, each individual CCU solves simpler tasks, which increases the overall speed of decision making. However, the complication of the management structure, due to the peculiarities of this scheme, can lead to significant delays or failures when transmitting commands between levels.The scheme of information flows between elements of such a system is shown in Fig. 2(b).

Systems with a centralized organization have such a common disadvantage as low fault tolerance. This is due to the presence of the CCU, the malfunction of which leads to disruption of the functioning of several agents or the entire system. Despite the possibility of using backup systems to maintain the performance of such systems, the costs of implementing such protective measures can be incomparably high. In systems with decentralized group management, there is no such drawback.

When using a decentralized management strategy, there is no CCU in the system, each agent has a computing center that has enough power to make decisions. When using such a scheme, the time spent on making decisions is minimized, as well as errors arising in the process of information exchange between agents of the group. One of the most important advantages of such a system is high fault tolerance - when one or more agents fail, the rest will continue to perform task.

Decentralized management strategy has more complex algorithms, each group member must make a decision that should ensure an approximation to the achievement of a common goal within the group. This implies a high intellectual level of all agents of the group, which implies the more complex task of optimizing the achievement of a goal within the group. Decentralized management approach can be divided into swarm and collective strategies.

The collective strategy is different from the swarm presence of the ability of group members to exchange information with each other. The organization of information flows in such a system is depicted in Fig. 3(a). The advantage of this approach is the possibility of increasing the efficiency of the group through the collective collaboration. However, this approach needs to ensure the protection of the information exchange channel, the violation of its work can lead to a violation of the data exchange between the participants.

The advantage of swarm strategy is high resiliency due to the lack of information exchange channel. The organization of information flows in a system with decentralized swarm control is shown in Fig. 3(b). When using this strategy, agents exist separately from each other and do not have the ability to communicate with each other, but they are able to analyze the state of the environment, and based on this, make decisions about further actions, Such actions should lead to achievement of a common goal, by changing the state of the agent and the influence of other agents on the environment.

Thus, after analyzing the existing approaches to managing of a group of UVs, it can be concluded that when using a centralized management strategy to organize safe passage for a group of intersection vehicles, there are certain risks. With an unexpected sharp increase in the number of UVs approaching the intersection, the CCU must quickly solve the problem of optimizing the passage, while taking into account the speeds and trajectories of approaching cars, to form optimal routes for them. Due to the above-described specific features of systems with centralized control, the simultaneous processing of large amounts of data can cause delays or malfunctions in the system, which can lead to a collision of UVs. This is unacceptable in the organization of a safe transport infrastructure, therefore, organizing travel using a decentralized management strategy for a group of UVs is seen by the authors of this work as more promising.

A fundamental factor in ensuring security during the intersection of intersections by a group of UVs is communication between group members. Based on the circumstances described, a decentralized collective management strategy was chosen to implement the model in the framework of this work. It is assumed that there are a number of intersections in the city, on which there is one TIO. TIOs carry out information exchange among themselves, jointly and decentralized solving the problem of traffic optimization at all intersections simultaneously. In the system there is no central object responsible for managing all intersections, each of the intersections is managed individually.

4 Model of Unmanned Vehicle System

Denote $C = \{c_1, c_2, \ldots, c_n\}$ - the set of UVs in the system. $I = \{i_1, i_2, \ldots, i_m\}$ - set of objects of transport infrastructure. The total square of travel sites $S = s_1 + s_2 + \ldots + s_k,$ where s_i - square of i's place (see Fig. 4). At the same time there are two options for dividing the total area of the city into elementary areas, they are shown in (1) and (2).

$$s_i \cap s_j = \oslash \tag{1}$$

$$s_i \cap s_j \neq \oslash \tag{2}$$

Each TIO interacts with all UVs, at the same time, the car c_j can interact with only one infrastructure object i_h. The main objective of this work is to set the task of organizing the movement of UV within the city and to build the optimal route, in which the actual time t_c of the vehicles movement is as low as possible $t_c \to min$. The reference time of movement t'_c is the time of movement of the vehicle in ideal conditions in the absence of interference and other vehicles that impede its movement $t_c \to t'_c$. Let t_k - k-th instant of time, $P_{ci} = \{p^1_{ci1}, p^2_{ci2}, \ldots, p^l_{ci}\}$ - the distance traveled by the vehicle during the actual travel time t_c. Then, it can be illustrated in (3) and (4):

$$\neg\exists\ t_k : P^{tk}_{ci} \cap P^{tk}_{cj} \neq \oslash \tag{3}$$

$$t_c \to t'_c\ \forall c \in C \tag{4}$$

In this case, the infrastructure object i_i generates a route for the vehicle c_i, taking into account the data received from the neighboring infrastructure facility i_j. The authors of the article identified the following criteria for overcoming a group of intersections for vehicles:

1. The number of cars ready to cross the intersection tends to zero at each intersection.
2. The actual speed of the car is close to the expected when driving in the city and when overcoming the intersection: $Speed^{avg} \to Speed^{need}$.
3. The area of occupied space at the intersection is minimal, $S_{occ} \to min$.
4. The time for a vehicle to cross an intersection at real speed is minimal: $t^{avg}_{cross} \to min$.
5. The total time spent on overcoming the constructed route with real speed also tends to minimum: $\sum^{t}_{cross} \to min$.

For clarity of the principles of the system and the possibility of developing a software simulator, the following simplifications are introduced:

- UVs strictly follow directions at the intersection;
- UV's computing devices know in advance their size, acceleration and deceleration dynamics, maximum speed;
- UVs strictly follow the instructions for choosing the trajectory, speed, place to stop, received from the TIOs;
- UVs and TIOs are equipped with communication devices, and it is understood that such devices provide ideal communication conditions, without delays, interference and data loss.

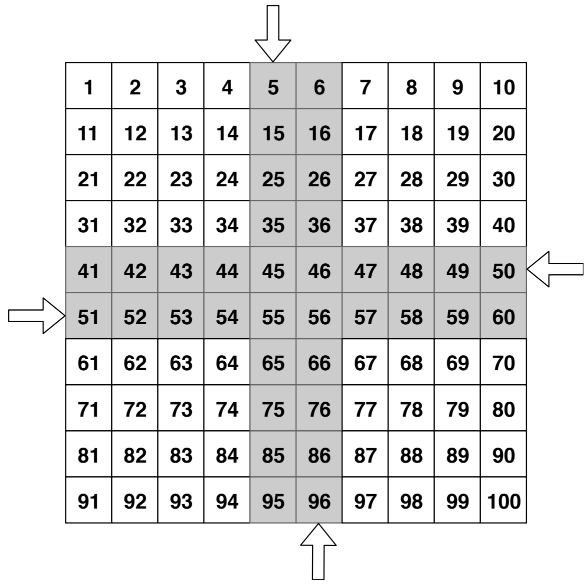


Fig. 4: Model of intersection and schematic representation of the direction of vehicles' movement

Thus, UVs and TIOs perform a number of inherent functions. Vehicles collect data on their technical condition and movement, data on the trajectory of other cars and transfer them to infrastructure facilities, store a plan of the city zone along which the route passes. Infrastructure objects accumulate information about the system, develop a plan for locally and globally optimal plans for the movement of vehicles in the city, monitor the performance of tasks by means of transport, and control the activities of other infrastructure objects if the city or automobiles they control are common.

5 Simulation Setup and Results

To evaluate the effectiveness of the proposed model, a software simulator was developed that imitates the movement of UVs within the city, in particular, their interaction at the intersections. The simulator involved creation of an intersection model and a UV model. Intersection model requirements:

- the allocation and state of all the elementary road sections are known to all the traffic participants;
- the beginning of the road should be situated on one of the borders of the simulated intersection, meanwhile its end should be on the opposite side, i.e. it is assumed that there are only straight roads which coordinates coincide with the coordinates of the elementary sections located in the same row (column);

– each road must belong to either vertical or horizontal type.

The intersection model includes the following set of characteristics: $\{c, r, R\}$, where c - number of columns that define the intersection; r - row amount defining the intersection; $R = \{R_1, R_2, \ldots, R_n\}$ - set of roads where the vehicle can move. In its turn, each road is characterized by a set of parameters $\{t, d, E\}$, where t - road type (vertical or horizontal); d - road direction (passing or oncoming); E - set of elementary sections defining the roadway. For the experiment, it was decided to limit to 4 lanes: two vertical (oncoming and passing) and two horizontal (oncoming and passing). Intersection size: 10×10 elementary areas. The general model of the simulated intersection is presented in Fig.4.

UV model assumes presence of the following characteristics:

– E - set of elementary sections based on a road map and the planned start and final positions of the UV;
– s - initial (maximum) speed. Speed is understood as amount of the elementary areas crossed by a UV per one conditional time discrete. In the conducted experiments maximum UV's speed is considered equal to 2, also, as the UV approached to the intersection, it reduced speed smoothly and passed the intersection on the minimum speed equal to 1;
– c - turning point if the final position of the UV is on a different road (taking into account the direction of road movement);
– ST - sequence of steps for the UV to go through the planned path (calculated on the basis of E, s, c; one step is passed in one conditional time discrete).

Conditions of the experiment:

– UVs can move in any direction within the roadway, according to the direction of the roads;
– the intersection model is spatially limited;
– the number of UVs simultaneously on the observed field is limited by the capacity of the current section;
– in case of a conflict (more than one UV pretend to the same elementary section contemporaneously), the UVs give way to each other, taking into account the maximization of the intersection capacity (see (5)):

$$\begin{cases} Y = \dfrac{\sum\limits_{l=1}^{L}\sum\limits_{j=1}^{N}\sum\limits_{i=1}^{M} n_{lji}}{M} \\ n_{lij} = \begin{cases} 1, \text{if } j^{\text{th}} \text{ UV is situated at the } i^{\text{th}} \text{ time discrete on} \\ \text{the } l^{\text{th}} \text{ elementary section, } n_{lji-1} \neq n_{lji} \\ 0, \text{otherwise} \end{cases} \\ Y \rightarrow max \end{cases}, \quad (5)$$

where N - number of UVs, passing the intersection; L - number of elementary sections at the intersection; M - amount of time discretes, for which N UVs passed the intersection;

– on the intersection the probability of the appearance of new UVs is given, the number of appearing vehicles is determined randomly.

For comparative analysis, a simulator based on conventional traffic lights control was prepared. Its properties are the following:

– the presence of traffic lights at the intersection;

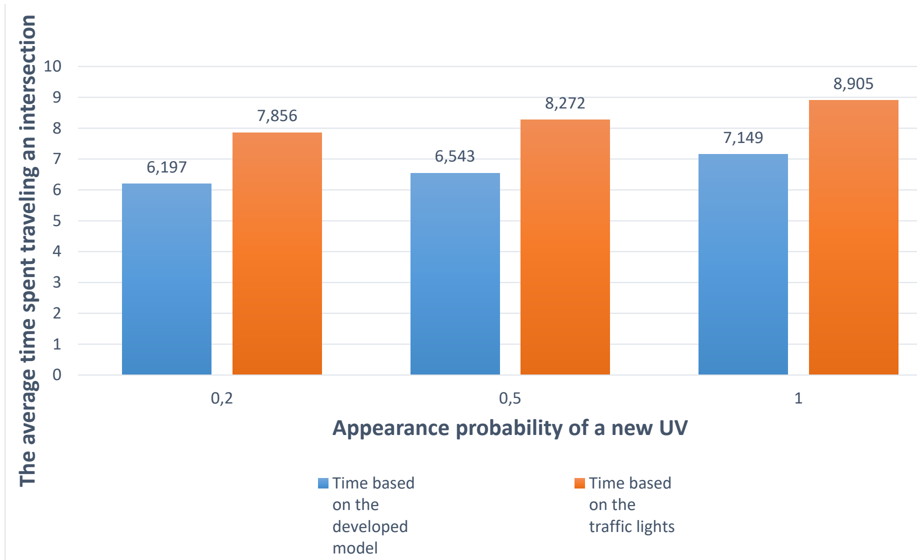


Fig. 5: The dependence of the average time spent on the passage of the intersection from the method of traffic control at the intersection used.

– calculation of ST is performed in the same order as in the model described above, but during the entrance into road intersection, the signal of the traffic lights is checked.

For the traffic lights control system at the intersection, the following cycles are taken: green light - 30 seconds, 4 seconds yellow, and 1 second all red.

The average time of the crossing of the intersection by UV was chosen as an indicator for comparing the quality of the algorithms. Three groups of experiments were conducted, differing in the appearance probability of new UVs on the intersection: $P = 1$ (at least one new UV appears), $P = 0.5$ and $P = 0.2$. The duration of each experiment is 1000 discrete time increments. After a series of independent launches for each group of experiments, the results took the form presented in Fig. 5.

According to the represented data, it is possible to note that the proposed model of the intersection control system allows to reduce the average intersection passing time per UV by an average of 20,5% in comparison with an intersection regulated by traffic lights.

6 Conclusion

As a result, in this work some approaches to the tasks of intersection management using objects of transport infrastructure were considered. The system was considered as a mobile robotic system, a model of interaction between unmanned vehicles and objects of transport infrastructure was developed. To test the effectiveness of the model, a software simulator was developed that allows simulation of the control of car traffic at the intersection using the developed model and using traffic lights. The results of the experiments showed that the developed model is more efficient than the use of traffic lights. In future studies, it is planned to model automobile traffic at several intersections within the framework of a smart city and to create a physical model for carrying out real experiments.

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