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Decentralized Cooperative Transport in Heterogeneous Robot Fleets Through Four Levels of Communication based on Omni-Curve-Parameters

Dezentraler kollaborativer Transport in heterogenen Roboterflotten durch vier Kommunikationsebenen auf Basis der Omni-Kurven-Parameter

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Changeable production needs an internal logistics system that can cope with various loads. Cooperative transport offers the possibility of transporting exceedingly large loads with a group of mobile robots. This paper addresses the research question of unifying cooperation considering each robots configuration using Omni-Curve-Parameters (OCP). OCP are designed to control robots with arbitrary wheel configurations and can be used for the control of cooperative transportation groups, by considering the group like a vehicle with many wheels. The approach is successfully validated on two omnidirectional robots. The emerging challenges concerning the communication between the participants lead to a multi-leveled communication model for a heterogeneous fleet, since exchanged data differs in its volume and its availability and time requirements. Consisting of the *global*, *local*, *cooperative* and *safety* levels, this model is a first draft for standardized decentral communication.

[Keywords: Cooperative Transport, Communication Model, Mobile Robots, Changeable production, Internal Logistics]

Eine wandlungsfähige Produktion erfordert ein Logistiksystem, das mit unterschiedlichen Ladungen umgehen kann. Kooperativer Transport bietet die Möglichkeit, übergroße Lasten durch eine Gruppe von mobilen Robotern zu transportieren. Dieser Beitrag befasst sich mit der Forschungsfrage, wie die Zusammenarbeit unter Berücksichtigung der einzelnen Roboterkonfigurationen mit Hilfe von Omni-Kurven-Parametern (OKP) vereinheitlicht werden kann. OKP sind für die Steuerung von Robotern mit beliebigen Radkonfigurationen konzipiert und können für die Steuerung von kooperativen Transportgruppen verwendet werden, indem die Gruppe wie ein Fahrzeug mit vielen Rädern betrachtet wird. Der Ansatz wird erfolgreich an zwei flächenbeweglichen Robotern validiert. Die resultierenden Anforderungen an die Kommunikation zwischen den Teilnehmern führen zu einem mehrschichtigen Kommunikationsmodell für heterogene Flotten, da sich die auszutauschenden Daten in ihrem Umfang, ihrer Verfügbarkeit und ihren zeitlichen Anforderungen unterscheiden. Bestehend aus den Ebenen *Global*, *Lokal*, *Kooperativ* und *Sicherheit* ist dieses Modell ein erster Entwurf für eine standardisierte dezentrale Kommunikation.

[Schlüsselwörter: Kooperativer Transport, Kommunikationsmodell, Mobile Roboter, Wandlungsfähige Produktion, Intralogistik]

1 MOTIVATION

The current shift towards changeable production requires internal logistics to be flexible. These properties cannot be met by classic material handling technologies such as continuous conveyors or rigidly line guided vehicles. The use of systems of freely navigating mobile robots allows a dynamic adaption of the material flow to changing operating conditions. An important component of these systems is interoperability with each other in heterogeneous fleets or with the periphery, e.g., transfer stations. A unified basis for cooperation means that vehicles can be deployed as required, depending on their capabilities and driving characteristics. This allows flexible task allocation and replanning. An example for the influence of such vehicle-specific capabilities is a forklift with a rigid rear axle, which is harder to maneuver in a narrow corridor than a small omnidirectional robot. This aspect should be considered in a crossing situation. The cooperation of different vehicles on a uniform basis, which considers their configurations, is essential for this.

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In the changeable production of the future, it is also necessary to transport loads that exceed the capabilities of a single robot. A unified description can be used not only for single robots, but also for a collaborative transport of larger objects. Such a scenario is shown in Figure 1 where two robots form a group to transport a large beam. A company which only owns smaller mobile robots might require to rarely transport larger loads. By enabling cooperative transport, this is also possible with the existing vehicles.

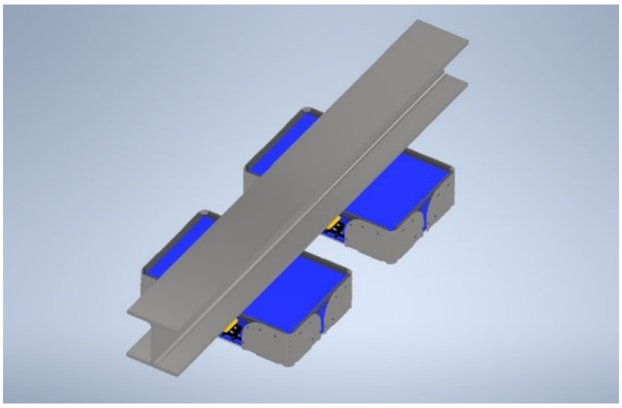

Figure 1.: A cooperative transportation group consisting of two robots transporting a large beam.

When additionally using varying vehicle types, the selection for transportation is possible depending on the maneuverability and payload of such a collaborative group, as well as the explicit path planning. When driving a curve, the maximum speed is set by the outermost vehicle whereas the minimal curve radius depends on the innermost vehicle. Based on these restrictions, the paths in an intersection situation between a mobile robot and a forklift truck can be planned. These scenarios are made possible by a uniform description and thus permit the flexible use of various vehicles in production.

Analyzing the task of cooperative transportation, this paper addresses the research questions of how a unified cooperation considering each robots configuration is possible. Based on a unified description, new challenges emerge concerning the communication between the participants. The task of developing a communication model enabling seamless integration and coordination of heterogeneous fleets for cooperative transportation constitutes the second research question.

2 Decentral Control in a Cooperative Transport

A standardized way of communicating with vehicles in a centralized manner is already being used in industry in the form of the standard VDA 5050 [1]. The increasing number of vehicles within a single fleet and the resulting complexity motivates the current research trend towards decentralized control [2, 3].

Especially for a collaborative transport, decentralized control is desirable since communication is limited to the participants of the task. For maximum flexibility it is desired to allow every arbitrary transportation formation. Existing approaches of such formation control describe the possibilities to enable such collaborative transportation [4, 5, 6]. These approaches for formation transportation have the disadvantage that the wheel configurations of the robots are not considered. The Consensus-based multi agent control considers robots as single integrators for example [4, 7]. Especially omnidirectional robots with three degrees of freedom are very complicated to control as a cooperative transportation group.

Combining heterogeneous robots with different wheels increase the difficulty even further [8], since the capabilities of every wheel must be considered. Also, limitations arising in formation are complex to calculate. Such limits also result from the wheel configuration of the robots, where wheels have limits for steering and speed.

Consequently, a decentralized standardized approach for arbitrary vehicles, such as robots, forklifts or cooperative robot transportation groups is needed, taking the wheel configuration into account, and uniformly presenting the limits computational efficient.

3 Cooperative Transport using the Omni-Curve-Parameters

Colomb et al. [9] present an approach to intuitively control arbitrary robots. The Omni-Curve-Parameters (OCP) defined there initially aim to describe any movements in a uniform and easily comprehensible way. Brenner at al. [10] extend this work and apply it to robots with various wheel configurations with the aim of achieving a universally applicable control approach. The speeds, optional internal configuration variables and their necessary ranges are determined for any wheel arrangement.

The application of the OCP standardizes and simplifies the control in comparison to generic approaches of mechanics. The calculation method avoids problems of numerical evaluation from the outset and can therefore be implemented in corresponding control systems in a practical manner [10].

In the previous works, OCP were used to control individual vehicles. In the context of cooperative transport in particular, their use also offers many advantages, by considering the transportation group as one vehicle with many wheels:

- The robots are controlled uniformly, regardless of their respective wheel configuration.

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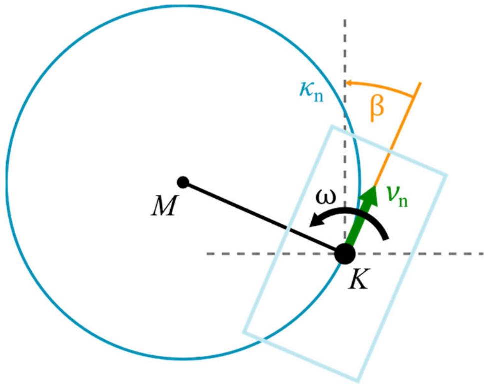

Figure 2.: Important variables using the OCP. The OCP are marked with: v_n as nominal speed, κ_n as nominal curvature and β as floating angle. Additionally, K characterizes the reference point, ω the angular velocity, M specifies the Instant center of rotation.

- Different vehicles can be easily controlled together. The degrees of freedom of each vehicle group are defined by the vehicle with the fewest degrees of freedom, making the control intuitive [9].
- The vehicles are all coordinated computationally efficient by being controlled using the same data. Only the OCP must be distributed so that the whole vehicle group performs a coordinated movement without much communication effort.
- The limits presented in [10] can be calculated and used directly for the entire cooperative transportation. This allows the path planning to generate possible paths for the corresponding vehicle configuration only based on the vehicle-specific boundary data.
- The path planning does not have to be done for each vehicle individually, but for the entire transportation group and then distributed to the vehicles accordingly. This results in shared computing capacity and also reducing the computation effort for path planning.
- Inaccuracies in the formation can be compensated locally by the vehicles rather than being communicated to a superordinate entity, reducing necessary communication.

Considering all these aspects, it becomes evident that OCP offers significant advantages when applied to cooperative transportation, resulting in the following concept.

4 Concept for Using OCP for Cooperative Transportation

In [9], the OCP are introduced for the control of arbitrary robots with a uniform set of control variables. The relevant parameters are shown in Figure 2. The aim of the OCP is the intuitive and uniform motion specification considering the degrees of freedom available in each case. After a systematic choice of the reference point K and determination of a limit curvature κ_g, the dimensionless nominal curvature κ_n abstractly describes the relation between rotation and translation, on a linear scale in the interval of $[-2 \dots 2]$. The linearisation is done to avoid singularities occurred by the radius R or the curvature κ. R and κ are defined for each section either in "narrow" or "wide" curves, which results in numerically manageable calculation and avoiding singularities in the process. Accordingly, the interpretation of the given velocity also changes depending on the context.
In addition to the nominal curvature κ_n, the float angle β also describes the configuration, thus the opportunities of the robot-chassis, but only in the omnidirectional case. It indicates the vehicle orientation superimposed independently to the trajectory curve of the reference point and is measured between the velocity vector $\underline{v}$ in the reference point K and the positive x-axis.
The third control variable, the nominal velocity v_n, on the other hand, does not change the configuration. It only scales the speed of the movement and is also expressed dimensionless in the interval of $[-1 \dots 1]$. The possible negative range corresponds to a reversal of direction. The extreme values refer to a maximum speed v_{max} determined by the vehicle, possibly depending on the situation. For the calculation of the linear or angular velocity (depending on the κ_n-range), the relevant product is therefore always

$$v_s = v_n \, v_{max} \quad \text{with} \quad v_{max} \geq 0$$

The switching of the velocity definition dependent on $|\kappa_n| \geq 1$ forms a continuous transition at the boundary curvature κ_g [9].

As described in [10] depending on these OCP it is possible to uniformly describe the limits of a robot. The kinematic structure and the limits of such a robot is shown in

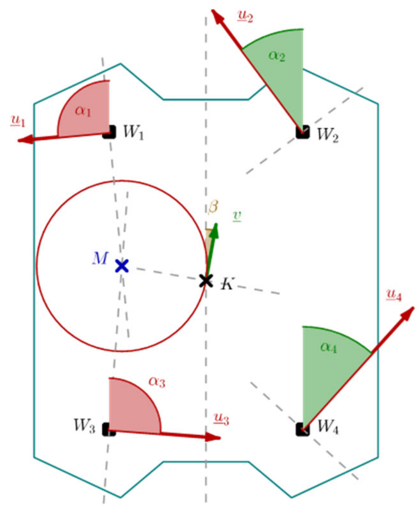

Figure 3.: Structure of one robot Scooty as depicted in [10]. The driving maneuver is marked as a red circuit. Driving this maneuver, the steering angles α_1 and α_3 of wheel W_1 and W_3 are red because the limit of $\pm 90°$ is exceeded while the steering angles α_2 and α_4 of wheel W_2 and W_4 are in the prescribed range. The velocities of the wheels are marked as $\underline{u}$.

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Figure 3. The red highlighted driving maneuver shown is not possible for the robot, because the wheels W_1 and W_3 have a lager target angle than their limit.

Using this definition of the OCP a transportation group of robots with different wheel configurations can be controlled according to this definition, by being treated as one robot with a lot of wheels.

Figure 4 shows a cooperative transportation of three robots driving a curve. The wheel configuration of the two small robots is two not steered wheels in the back and one steered wheel in the front. The big robot has four steered wheels. The desired trajectory of the cooperative transportation group is marked in red. All the wheels pole rays must intersect in the instantaneous center of rotation (ICR) so that the cooperative transportation group performs a defined movement.

In such a cooperative transportation with robots consisting of different wheel configurations the wheels, which are not steered, must lie on one axis. In this case the ICR is lying on the axis of these not-steered wheels. Thereby the curvature κ_n moves the ICR on this axis. In case of configurations only consisting of steered wheels the robots are controlled with all three OCP. The slip angle β rotates the ICR around the reference point K wherefore the ICR is placeable everywhere in the space, only depending on the boundaries of the wheels.

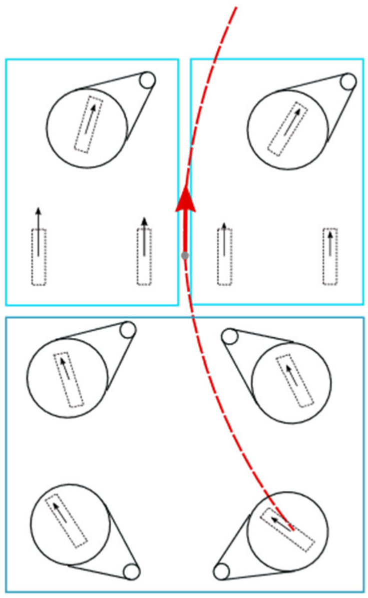

Figure 4.: A cooperative transportation group consisting of two smaller robots with one steered wheel in the front and two not steered but powered wheels in the back and a large robot with four steered and powered wheels. The desired trajectory is marked in red.

To show the result of such a cooperative transportation the approach is applied on two *Scooty* vehicles, *Scooty 06* and *Scooty 07*, shown in Figure 5. *Scooty* vehicles are built with four steered wheels, which can rotate to a limit of ±155°.

Figure 5.: Two omnidirectional robots, Scooty 06 and Scooty 07, driving as a cooperative transportation group. A joystick is used to communicate the OCP to both robots. The distance of the robots is 100mm.

Driving as a cooperative transportation group the two *Scootys* are set to a constant distance of 100mm, which describes the cooperative transportation formation. The point K is in the geometrical middle of the two robots. To describe the limits of this cooperative transportation group the sampling in the nominal curvature - slip angle space is performed. The result is shown in Figure 6.

The blue surface marks the configuration restrictions of the transportation group (see also [10]). It is noticeable that compared to the limits of a single *Scooty*, as shown in orange, the restricted space of the group is much bigger. This is due to the reference point lying in the geometrical middle between the two robots. This causes the inner vehicle to reach its steering angle constraints faster when driving around curves. Furthermore, if the slip-angle is zero all curvatures are possible.

It has been shown that OCP are suitable for use in cooperative transport. To what extent this can be applied to

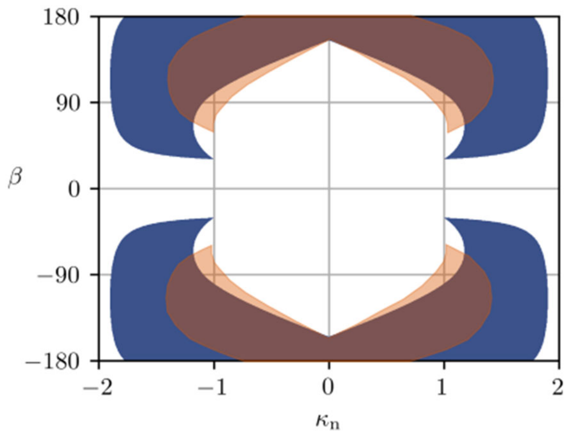

Figure 6.: Limit configuration of the cooperative transportation group plotted in the nominal curvature - slip angle space. The restriction of the two Scootys as cooperative transportation group is marked in blue. The restriction of a single Scooty is indicated in orange, as defined in [10].

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the different steps necessary during the entire process is outlined in the following chapter.

5 Phases for cooperative Transport

In a logistics environment, vehicles are not always in a fixed formation right from the start. The group must form dynamically, according to the load to be transported, come together and dissolve again after successful processing. This process can be divided into four phases, as shown in Figure 7. OCP play a central role in each of these phases.

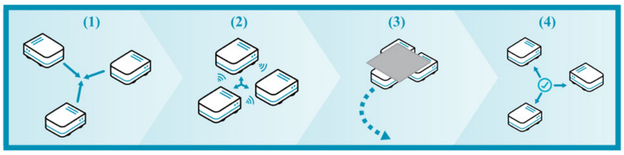

Figure 7.: Illustration of the phases of a collaborative transport consisting of (1) configuration, (2) initialization, (3) cooperation and (4) finalization of the corresponding groups of mobile robots.

In the first step of the process of transporting arbitrary transport goods a suitable formation of vehicles must be identified. Both the viable vehicles from a potentially heterogenous fleet and a suitable formation need to be determined. Here, factors such as size, geometry and possible specific requirements of the load as well as the current traffic situation and map layout need to be considered. The OCP approach can either be used to check if a route is viable for a given formation or directly determine possible formations that can carry out a given route.
Subsequently the vehicles need to create the determined formation at the pick-up location. This initialization represents a traffic management challenge in a relatively small space. Again, the OCP can be used to efficiently determine the trajectories for each vehicle considering their respective capabilities.
Once in formation the OCP based approach not only unifies the control of the individual vehicles within the composition but since they now act as a single entity the handling of other traffic management situations such as the passing of each other in narrow corridors are also simplified. Any necessary replanning caused by obstructions or scheduling changes can also be handled using the same OCP based method.
Lastly in the finalization phase the dissolution of the formation considering all limitations of the individual vehicles and their respective desired destination can also be managed using the OCP approach.

The use of OCP will provide a uniform way to realize cooperative transport by making the control independent of the individual wheel configurations. This facilitates carrying out transportation tasks using vehicles from different manufacturers. In the process, new challenges emerge concerning the communication between the participants. Consistent with the proposed unified control using OCP, a communication model enabling seamless integration and coordination of heterogeneous fleets is presented in the following.

6 Communication Model

Cooperative transportation requires the exchange of information between entities at different levels. Entities can be robots or other participants, like transfer or charging stations. Several entities can also unite to form a logical entity that acts and communicates as one, as it occurs for a cooperative transport. Depending on the scope of the information exchange, the communication model differentiates between a *global*, *local*, *cooperative* or *safety* level. The levels represent to which extent the exchanged information should be available to other entities rather than the actual physical distance. This distinction is necessary because exchanged data differs in its volume and its availability and time requirements, imposing different hardware and software specifications. The exchange of planned routes between robots, for instance, must be distinguished from the exchange of a joint emergency stop or the synchronization of control data. The communication model consisting of the four levels is shown in Figure 8.

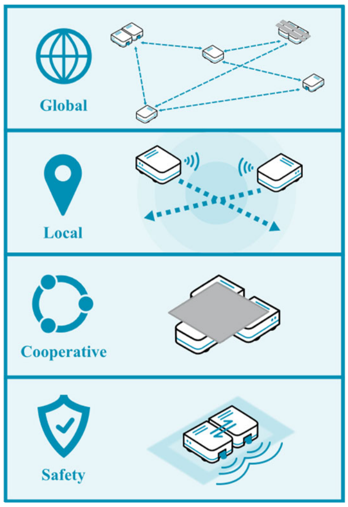

Figure 8.: Depiction of the proposed communication model.

Any communication concept that requires information exchange between arbitrarily positioned entities in the system is considered part of the *global* level. However, if the information is to be provided only to entities that are in spatial or logical proximity, the communication takes place on the *local* level. This leads to a targeted data exchange by reducing the number of recipients and thus the communication overhead. To facilitate the execution of cooperative tasks, near real-time communication with enhanced robustness is essential. Since this was not necessary before, the *cooperative* level is introduced. Enabling general collaboration between robots, safety relevant data is to be exchanged between them. For instance, when robots operate in immediate vicinity, there is a need to adjust their safety fields. A safe communication of their respective positions would allow this. This and other safety relevant procedures pose even stricter requirements for communication. To distinguish this type of communication from all others, the *safety* level is introduced.

Table 1.: Overview of the different levels and corresponding responsibilities, other possible processes, the resulting requirements and the scope of validity.

Level	Responsibility for Cooperative Transport	Mobile robot processes	Requirements	Scope of validity
Global	Finding a suitable formation	Task (re-)allocation, Reservation of routes, map updates, broadcasting global positions, warnings, registration & deregistration of participants	High bandwidth, high range and coverage	Entire facility
Local	Creating the determined formation	Traffic management (crossings, priority, congestion avoidance, obstacle report), communication with periphery (transfer stations, gates, charging stations)	High bandwidth, medium range	Within current scenario boundaries
Cooperative	Maintain formation, replanning of route, guaranteeing that the composition acts as one entity	Vehicle grouping for more efficient traffic management (tugger trains), mobile manipulation	Low latency, frequent updates, stable connection	Within formation
Safety	Adjusting safety fields to formation and possible load overhang, joint emergency stop	Adjusting safety field for passing vehicles	Comply with safety regulations	According to specific regulation

The model presented here makes it possible to represent decentralized communication in the various steps of collaborative transport (see chapter 4). But it can also represent additional approaches from the research field of decentralized control of mobile robotics systems. For example, a market-based approach to task allocation will perform the necessary communication for auctioning with participants on a *global* level. The negotiation of priority at intersections, as is already possible in various robotics systems today, can be executed on the *local* level with the respective participants. And the necessary synchronization of a mobile manipulation from one vehicle to another is done on the *cooperative* level. However, this model is not intended to force decentralization at any price. For some approaches, such as managing the reservation of driving paths, a centralized system may still be a better solution. In its implementation, the model should offer the freedom to incorporate existing centralized and decentralized structures and be modular enough to incorporate future approaches easily. In accordance with the VDA 5050 for central communication between mobile robots and a control system, this model is intended to provide a first draft for a standard in uniform decentralized communication between entities.

Table 1 describes the different levels of the communication model in more detail. In addition to the responsibility of this level during cooperative transport, a selection of possible further processes in mobile robotics is presented, which benefit from a uniform model of the corresponding level. Furthermore, the requirements according to the defined tasks were qualitatively determined and provided. The scope of validity defines the spatial and logical scope of the corresponding levels.

7 Conclusion and Outlook

This paper addresses the research question of unifying cooperation considering each robots configuration. This is answered by considering the task of a cooperative transportation, using Omni-Curve-Parameters (OCP). OCP are designed to control robots with arbitrary wheel configurations using only three parameters thus simplifying calculating their steering restrictions. This basis allows the cooperative transportation using formations of arbitrary robots intuitively defined by the vehicle with the fewest degrees of freedom. The limits presented in [10] can be calculated for a formation and used directly for the entire cooperative transportation group.

This paper shows the implementation on two omnidirectional *Scooty* robots forming a transportation group. The advantages using OCP, e.g., efficient calculating the bounds of this transportation group are shown.

The emerging challenges concerning the communication between the participants are analyzed based on the cooperative transportation process. This leads to the developing of a communication model enabling seamless integration and coordination of heterogeneous fleets. Four different levels of communication are defined, since exchanged data differs in its volume and its availability and time requirements. On the *global* level, information relevant to all other participants can be communicated, while at the *local* level, this information is only shared in a defined, spatially or logically close group. On the *cooperative* level, information necessary for cooperative tasks is exchanged in the group of participants. Safety relevant procedures pose even stricter requirements for communication, leading to the *safety* level. The proposed model can be applied to additional approaches in decentral control strategies in multi robot systems. It is intended to provide a first draft for a standard in uniform decentralized communication between entities.

Ongoing research focusses on integrating heterogeneous robots to perform a cooperative transport, calculating trajectories based on OCP limits, developing a control strategy to prevent drifting apart during transportation and dealing with the question of safe communication. The occurring communication efforts are mapped and implemented according to the presented communication model.

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