Distributed Coordination and Task Assignment of Autonomous Tandem Rollers in Road Construction Scenarios

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Abstract -

Automation in construction is a highly active field of research with promising prospects for more efficient construction processes. This paper presents a novel behavior-based approach for distributed coordination of autonomous tandem rollers. Hereby, a detailed road representation and concepts for tandem roller and paver interaction as well as distributed task assignment are presented. The concept has been tested in a simulated road construction environment on the virtual B10 highway, Germany and compared to real construction data.

Keywords -

Off-Road Robotics, Behavior-Based Control, Multi-Robot Cooperation, Automated Road Construction

1 Introduction

The domain of construction industry strongly benefits from recent developments towards high-performance assistance systems and autonomous machines [1]. Complex construction tasks can be performed with higher efficiency, safety, and quality despite the continuously increasing complexity of the tasks. The area of road construction offers a high potential to profit disproportional from automation because collaborating machines have to be organized according to available time windows, their capabilities, and clearly defined tasks.

The automation of road works raise challenges subjected to the environment, infrastructure, and AI skills of smart machines. For instance, the construction environment changes permanently which challenges a robust and safe robot control. Additionally, the unstructuredness, varying environmental conditions, and fluctuating illumination affect sensor systems negatively. While it is still an open research problem, behavior-based control systems (BBS) present a promising approach to conquer these challenges. They are highly modular and run parallel components with overlapping functionality to increase robustness [2]. Also, swarm robotics are widely studied and there exist various approaches to handle the complex coordination tasks of robot interaction [3].

A prerequisite for robot interaction and collaboration is the availability of communication infrastructure. The project *Autonomous Mobile Machine Communication for Off-Road Applications* (5G-AMMCOA) funded by the German Federal Ministry of Education and Research (BMBF) focuses on the development of mobile 5G-Islands for a local, infrastructure independent communication and its impact on autonomous fleet management.

This paper presents a novel behavior-based control approach for a distributed coordination and task assignment of autonomous tandem rollers in a road construction scenario. Sect. 2 provides an overview to state of the art in autonomous road construction and multi-agent robotic systems. The integrated behavior-based control architecture serving as a base for the presented approach is introduced in Sect. 3. Then, the considered road construction scenario is described in Sect. 4. Sect. 5 introduces the formal description of a road model exploited in the control approach. The corresponding task description for tandem rollers is stated in Sect. 6. A behavior-based, distributed task assignment concept is proposed in Sect. 7. Sect. 8 presents experimental simulation results to evaluate the approach. Finally, Sect. 9 summarizes and concludes.

2 Related Work

In the recent past, there have been various research activities towards the automation of road construction and coordination of machinery. As early as 1998 the GNSS-based assistance system *AutoPave* was developed to map tandem roller trajectories on individual road segments for an improved quality and future automation [4]. Nearly twenty years later advances in automation technology promote the developments towards autonomous road construction. Control concepts have been developed to achieve an autonomous tandem roller navigation that is coordinated with a paver [5] as well as trajectory planning strategies for rolling patterns on asphalt [6]. Design concepts for future tandem rollers envisage machines without a cabin, where a fleet of robots which mimic a manned master machine is operated by a single human [7]. The *SmartSite* project targets real-time path-planning of multi-agent compactors systems [8]. Next to improvements to the overall logistic chain, a focus is directed to sensor data exchange and adaptation to environmental changes. Subsequently, the project *Road Construction 4.0* builds upon *SmartSite*'s results and aims to further improve the intelligent control of construction processes [9].

Behavior-based and bio-inspired multi-agent systems have been well studied in the past [10]. The ALLIANCE architecture [11] presents a fault tolerant system for heterogeneous robot interaction. Each robot uses a motivational behavior to activate a task and suppress the task assignment of collaborating robots. The authors of [12] suggest a distributed swarm coordination approach which uses hybrid automata for behavior coordination through processing time- and event-based components to coordinate robots. A safety concept for robot collaboration is suggested by [13] and combines dynamic safety contracts with behavior-based control. Hereby, unsafe autonomous operations are limited through a safety cage.

3 Integrated Behavior-Based Control

The integrated behavior-based control (iB2C) architecture ([14], [15]) developed at the Robotics Research Lab (RRLab), TU Kaiserslautern, is used as the underlying software architecture for the presented approach due to its advantages concerning robustness and modularity. An iB2C behavior network consists of three main components (Fig. 1).

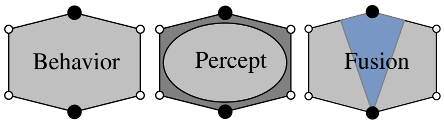

Figure 1. Main components of iB2C [15].

Standard behaviors are applied within a control context. Therefore, the complex tasks are decomposed into rather simple, but yet self-contained sub-tasks that can be implemented by individual behaviors. Thereby, partially overlapping functionality increases the system robustness, while the inherent modularity fosters reuse and extensibility. Similarly, percept behaviors are used to realize perception tasks including the data quality assessment. Competing control (perception) tasks are orchestrated by exploiting predefined fusion behaviors. All behavior components offer the same standardized interface for component coordination. Thereby, the behavior component's activity plays an important role since it represents the relevance of the component in the current system state, which can be externally adjusted via stimulation and inhibition by other modules.

4 Scenario

An important scenario which offers a lot of potential for optimizations in efficiency and quality by exploiting automation is the paving and compaction process of an asphalt layer in road construction. The road is layed out by a paver and compacted by a group of cooperating tandem rollers. To ensure a good compaction result, the rollers have to complete several tasks:

- Right behind the paver, the main compaction occurs. Rollers will compact the asphalt by applying a certain amount of passes, possibly with active drum vibration.
- Further back, rollers finish the surface statically.
- On open sides of the road, a roller has to press the edges with a special edge cutter tool.
- If a top layer is being built, a roller with a chip spreader might have to apply chip.

The process is dynamic, i.e. there is no fixed plan beforehand defining which task will be completed by whom at which time. There are several necessary events which will interfere the process during the day:

- The paver might have to slow down or stop because of a lack of material supply, caused e.g. by a traffic jam or a mixing plant failure.
- Rollers have to refill their water. Since the water tank is usually not moved during the day, the rollers have to travel back some distance to refill.
- Special jobs, like pressing the edges or seams, do not have their own dedicated machine - they are done in between.

5 Road Representation

An automated road compaction process requires a common representation for data exchange. One asphalt paver acts as the primary vehicle and stores road construction data collected during the paving process. The participating pavers collect data about the asphalt area like temperature and compaction. Collaborating rollers gather sensor readings as compaction and temperature to update already existing information. An overview of the road model is depicted in Fig. 2.

A road $\mathcal{R}$ has a set of lanes $\vec{\mathcal{L}}$ corresponding to the number of pavers. A lane $\mathcal{L}_i$ corresponds to the paver with ID i. Additionally, the road has longitudinal seams which connect and delimit lanes. A seam $\mathcal{S}_j$ is shared by

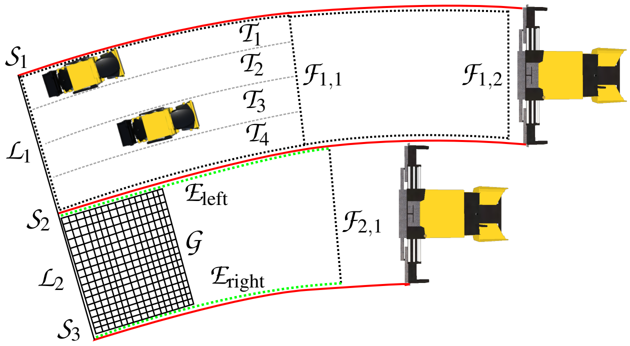

Figure 2. Road $\mathcal{R}$ with lanes $\vec{\mathcal{L}}$, seams $\vec{\mathcal{S}}$, fields $\vec{\mathcal{F}}$, edges $\vec{\mathcal{E}}$, grids $\vec{\mathcal{G}}$, and tracks $\vec{\mathcal{T}}$.

neighboring lanes. Therefore, there exists one additional seam with respect to the number of lanes

$$\mathcal{R} = \left(\vec{\mathcal{S}}, \vec{\mathcal{L}}\right), \text{ where } ||\vec{\mathcal{L}}|| = ||\vec{\mathcal{S}} + 1||. \tag{1}$$

Each road lane $\mathcal{L}_i$ contains a vector of fields $\vec{\mathcal{F}}$. Thereby, each field $\mathcal{F}_{i,k}$ has a maximum length of 25 m. It is defined as a polygon based on the paver's screed points $\vec{\mathcal{P}} = \overrightarrow{(p_{\text{left}}, p_{\text{right}})}$ during paving. Therefore, the field's width varies over time depending on the construction process. Exemplary, the minimum screed length for a BF 800 C paver is 2.55 m and 10 m maximum.

A field $\mathcal{F}_{i,k}$ contains two edges $\mathcal{E}_m$ with $m \in \{\text{left}, \text{right}\}$ and a grid $\mathcal{G}$.

$$\mathcal{F}_{i,k} = \left(\mathcal{E}_{\text{left}}, \mathcal{E}_{\text{right}}, \mathcal{G}\right) \tag{2}$$

Each edge is represented as B-spline which is appended by the respective paver's extending screed outer point p_{left} or respectively p_{right}. An edge is also a part of the corresponding seam $\mathcal{S}_j$.

The grid $\mathcal{G}$ has a resolution of $r = 10$ cm and stores construction relevant data such as the asphalt insertion time or respectively the last sensor update t_{up}, temperature estimation time t_{est}, measured stiffness c in MN/m^2, asphalt temperature T_{asph}, and asphalt temperature estimate T_{est} in °C. The temperature estimate is based on the last temperature measurement by the rollers or paver.

$$\mathcal{G}_{l,w} = \overrightarrow{\left(t_{\text{up}}, t_{\text{est}}, c, T_{\text{asph}}, T_{\text{est}}\right)} \tag{3}$$

The longitudinal grid index l depends on the current field length, while the index w on the respective paver screed width. Each grid $\mathcal{B}$ represents an detailed map of the current road section. Rollers utilize it for path planning under the consideration of the compaction effort, compaction time, temperature, and the current compaction state. Therefore, each field and respectively grid can be converted into a set of tracks $\vec{\mathcal{T}}$. A track $\mathcal{T}_n$ is a planned compaction area of a roller. Therefore the track's width depends on the area covered by a roller's drum or crab steering. For instance, the BW 154 tandem roller class has a drum width of 154 cm while BW 174 has 174 cm respectively. Additionally, the width can be extended through crab steering by 135 cm.

5.1 Temperature Model

A detailed description of asphalt cooling is provided in [16]. The most relevant parameters that influence the cooling behavior are the layer thickness λ, asphalt temperature T_{asph}, wind speed v_{wind}, and ambient temperature T_{amb}. In the previously described road representation, the asphalt layer thickness is provided by the road object $\mathcal{R}$ itself. Hereby, it is differentiated between base course, binder layer, and wearing course. The layer's thickness λ can be set as a parameter depending on the given class. This is also relevant for later compaction, vibration, and chip spreading. As mentioned before, T_{asph} is stored within the lane's grids $\mathcal{G}$. The parameters v_{wind} and T_{amb} are determined externally and set up in advance or measured by additional sensors. To estimate the temperature at time point $t_{\text{est}} = t_{\text{up}} + \Delta t$, which is Δt seconds after the actual measurement sensor measurement time t_{up}, the estimation of the temperature flow $\dot{Q}$ is exploited:

$$\begin{aligned}\dot{Q} = 7.4 + 6.39 \cdot v_{\text{wind}}{}^{\frac{3}{4}} \left(T_{\text{asph}} - T_{\text{amb}}\right) + \\ + 53.83 \cdot 10^{-9} \cdot \left(T_{\text{asph}}^4 - T_{\text{amb}}^4\right) - 680\end{aligned} \tag{4}$$

It follows

$$T_{\text{est}}\left(T_{\text{asph}}, \lambda, v_{\text{wind}}, T_{\text{amb}}, \Delta t\right) = T_{\text{asph}} - T_{\text{drop}}, \tag{5}$$

where the temperature drop T_{drop} for the duration Δt is

$$T_{\text{drop}} = \frac{\int_0^{\Delta t} \dot{Q} \, \mathrm{d}t}{2640 \cdot \lambda r^2}. \tag{6}$$

Analogous, a maximum time window until a certain temperature is reached can be determined. This is especially relevant for the asphalt compaction planning.

5.2 Asphalt Compaction

The asphalt compaction depends on different factors as asphalt composition and temperature. Furthermore, it can be differentiated between pre-, static and dynamic compaction. Additionally, the machine used for road works influences the compaction process.

Mix proportions are assumed to be constant in the following. This is also a prerequisite of the previously described temperature model, where factors like asphalt density and thermal conductivity are included as constant factors. The current asphalt temperature determines the compaction effort and defines time frames for compaction. In general compaction should start as early as possible. The effort $\mathrm{Eff}(T)$ depends on the temperature T and is defined as

$$\mathrm{Eff}(T) = \begin{cases} T < 80\,°\mathrm{C} & \text{too cold} \\ 80\,°\mathrm{C} \leq T < 100\,°\mathrm{C} & \text{stop range} \\ 100\,°\mathrm{C} \leq T < 140\,°\mathrm{C} & \text{optimum} \\ 140\,°\mathrm{C} \leq T < 160\,°\mathrm{C} & \text{start range} \\ \geq 160\,°\mathrm{C} & \text{too hot} \end{cases} \quad (7)$$

Therefore, the duration ΔT_{stop} denotes the time until the asphalt is too cold based on the previously described temperature model.

The road's required number of transitions to achieve a feasible compaction can be estimated beforehand according to the vehicle class. It can be differentiated between static and dynamic compaction. Hereby, static compaction is used to achieve a minimum precompaction (too low compaction value) or for ironing (high compaction value). Dynamic compaction utilizes drum vibration of the roller. Usually, low and high amplitude modes are available. The low amplitude vibration is used for the wearing course and the binder layer, while the high amplitude is used for the road's base course. Additionally, there exist different tandem roller classes as for instance 4t, 7t, or 10t vehicles. Hence, the transition count and compaction amount depends on the roller class. Exemplary data is provided by [17]. In the following, the number of transitions is used to estimate the current compaction.

The optimum compaction speed is inbetween 1 and 2 m/s. This is used for scheduling of tracks based on the compaction priority. The compaction amount and compaction effort define the priority of a track $\mathcal{T}_n$ under the consideration of remaining time. Therefore fields with a low ΔT_{stop} value and low compaction amount c are prioritized high.

6 Road Construction Approach

The general road model of a specific construction site depends mainly on the available pavers. Usually, several rollers of different build types are available. Their usage and usability depends on their properties, the given construction scenario and the task requirements.

6.1 Roller Tasks

Aside from the *compaction* task itself, rollers have several other tasks to fulfill. They have a limited supply of diesel and water, which is consumed meanwhile. Due to the relevance of machine availability, *refueling* is considered as an own task and enables to remain operational even on low supplies. Additionally, resource rerouting may be required. Thereby, a roller *navigates* to a target position. Under certain conditions a roller may be *idle*, e.g during an oversupply. Hereby, it monitors the construction progress and can be requested to rejoin the fleet and actively work on another task.

6.2 Roller Skills

The larger a road construction site, the higher is the probability that there exist unequal rollers which belong to another vehicle classes or are equipped differently. Each roller has some tasks it excels at and some where it is inadequate for. In order to be able to compare rollers, different skills have to be considered. They are described as a percentage of the task feasibility, which influences a later assignment. This guarantees that a roller is able to perform a task in an adequate manner. Exemplary skills are edge compaction, chip spreading, pre-compaction, or narrow curve compaction.

6.3 Compaction Tasks

Road compaction is divided into sub-tasks which are accomplished by the rollers. An initial task is the processing of the *latitudinal seam* which provides a suitable connection to another street segment. Hereby, a roller's drum has an overlap of approximately 20 cm with the hot asphalt while the other part remains on the connected segment. A main tasks is the *track* compaction. It is also related to *longitudinal seam* processing. Each track overlaps with its neighbor for several centimeters in order to achieve an even connection. Additionally, the *ironing* of tracks is important. Final tasks are *edge compaction* and *chip spreading*. While chip spreading is essentially identical in the movement planning to track compaction, edge compaction depends mostly on the type of edge. Usually, edge processing requires a specific tool as a cutter or conical roll mounted on the vehicle. Furthermore, edges need to be driven as accurately as possible. Hence, those tasks are especially dependent on the roller's capabilities.

6.4 Compaction Strategies

The exists a variety of asphalt compaction strategies depending on the number of available rollers. In general, a single roller usually compacts a track, seam, or edge on its own. At the end of each track, a curve is driven towards the center of a seam to create a matrix within the asphalt to improve robustness.

A practical oriented swarm compaction approach is used in the following. Two rollers compact directly behind the paver, while a third roller irons a field behind. If a front roller has to leave the formation, the rear roller can catch up.

6.5 Compaction Errors

The final roads quality depends heavily on the avoidance of compaction errors. A major factor is the road's temperature since the compaction of too hot asphalt damages the surface, while too cold asphalt prevents the completion of compaction, respectively. Furthermore, the application of an unsuited roller class, e.g. too heavy vehicles, can introduce bow waves. Similarly, severe fractures may appear at the rolls edges. Also, shear forces have to be considered and sharp turns on the asphalt prevented. An insufficient bandages sprinkling may cause the material to stick on the rolls. Usually, a damaged section of the road forces a complete reconstruction and has to be prevented by all means. Therefore, error avoidance is explicitly considered during task assignment.

7 Distributed Task Assignment

Road compaction involves many vehicles which have to be coordinated accordingly. The construction process consists of many tasks that are distributed between machines. In contrast to a strict hierarchical procedure, where a master defines every task and the corresponding assignment, human workers follow a more self-determined way of task-fulfillment. In the following, a distributed approach for task assignment is proposed. Here, robots determine their suitability for a task self-directed. Each robot suggests its feasibility for a given task to an inter-robot behavior network which selects the most suited robot.

7.1 Communication of Construction Vehicles

The REACTiON architecture [18] provides a framework for robust and safe off-road navigation of commercial vehicles using a behavior-based approach. REACTiON provides basic perception and localization skills [15], as well as a low-level collision avoidance [19] to the involved robots as tandem rollers, or paver. Furthermore, a behavior-based communication approach adapts transmitted data according to the available bandwidth [20].

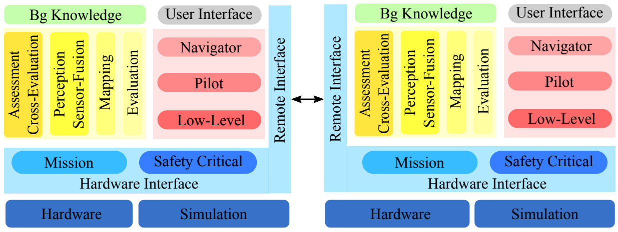

Figure 3. Robot communication using REACTiON remote interfaces.

Robot communication is realized by an extended REACTiON architecture exploiting remote interfaces (Fig. 3). Hereby, a remote interface equals a standard hardware interface. Subsequently, collaborating vehicles and transmitted sensor data can be considered as external sensors. Additionally, higher level information can be exchanged. Therefore, it is possible to span a behavior network across vehicles.

7.2 Paver Road Update and Task Assignment

The paver is the central element of the road construction process. Therefore, it manages the communication of the fleet and creates a mobile 5G-island [21]. As part of the inter-vehicle behavior network, it distributes all road construction and compaction tasks.

Fig. 4 depicts the part of the distributed BBS running on the paver. The *Perception* system provides information about the paver's *Screed* like pre-compaction, temperature, and current screed extension. *Pose* data is used to determine the exact screed location under the consid-

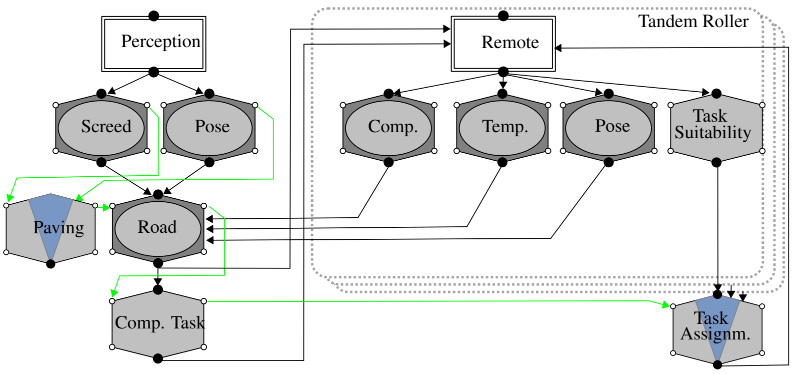

Figure 4. Paver behavior network for road model maintance and task assignment. Tandem rollers connect remotely to the paver and update road information. Task assignment uses a fusion behavior to select a roller.

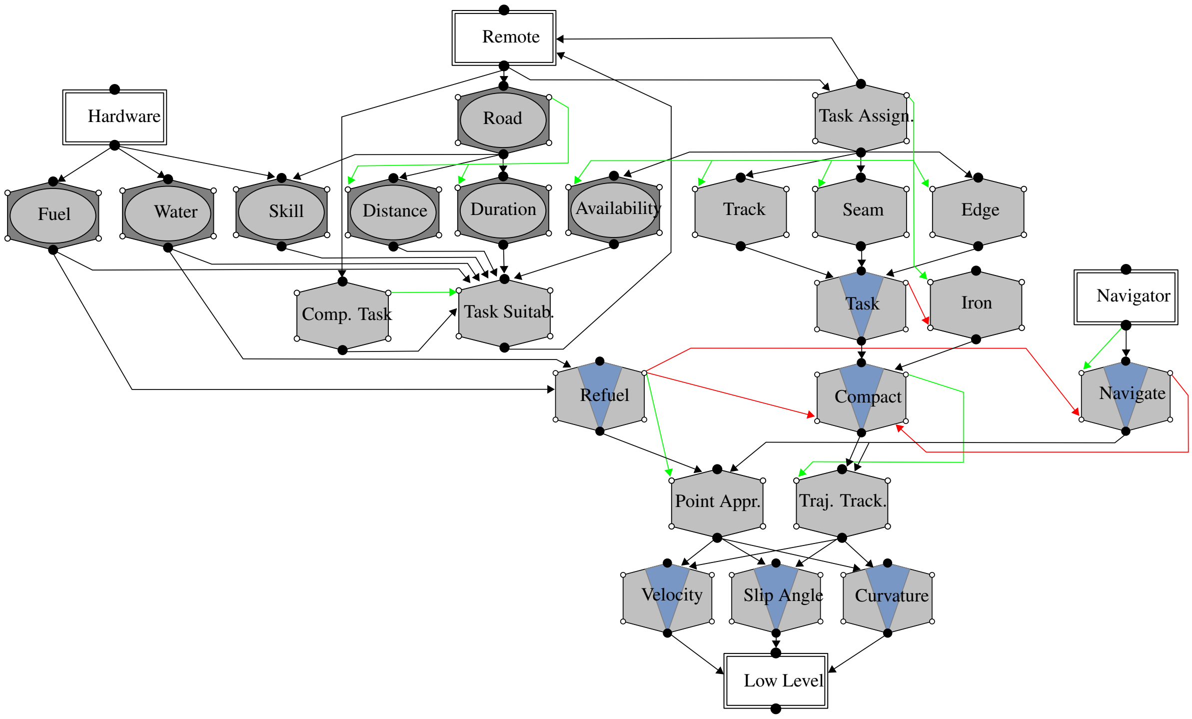

Figure 5. Tandem roller behavior network for road compaction. Properties as fuel, water level, skill, distance to a location, availability, and task duration are considered to determine the individual suitability to execute a task.

eration of localization sensor quality estimates. A *Road* model is maintained during the *Paving* process by successive updates of the paver's screed data. Additionally, collaborating tandem rollers provide road relevant data like the measured *Compaction*, *Temperature*, and the roller's *Pose* through the *Remote* interface. Compaction and temperature data update the temperature information and estimate contained by the road's grid content.

The paver determines the next *Compaction Task* which has to be performed by a roller. Hereby, a priority queue schedules the next task based on the criticality resulting from time constrains, compaction effort, and temperature. The compaction task is sent together with a task identifier to all collaborating rollers through the remote interface. Each roller responds with an estimate about its *Task Suitability* and the roller ID. The suitability is encoded within the behavior's activity and is determined individually by each roller. Thereby, factors as the current task, roller skills, fuel level, distance to the task location, and availability are considered. The *Task Assignment* uses a maximum fusion to select the best suited roller. The winner is acknowledged and adds the task to its task queue.

7.3 Tandem Roller Task Request and Execution

The task assignment among tandem rollers is a distributed process through the connected inter-vehicle behavior network. An extract of the network is depicted in Fig. 5. A roller can fulfill three main actions. It can *Refuel Fuel* or *Water*, *Compact*, or *Navigate*. The latter bases on the output of the *Navigator* interface. The vehicle is idle if there exists no activity in the network. Each of the three tasks provides either a target destination to a *Point Approach* behavior or a spline which is followed using the *Trajectory Tracking* behavior. Both navigation behaviors provide a *Velocity*, *Curvature*, and *Slip Angle* to the *Low Level* control interface.

Each roller retrieves a *Compaction Task* and the updated *Road* model from the *Remote* interface connected to the paver. Thereby, the individual *Task Suitability* is estimated under the consideration of the *Fuel* and *Water* level, as well as its *Skill* for the task based on the *Hardware* information. Additionally, the spatial *Distance* is considered to prefer tasks nearby. Furthermore, the *Duration* of a task and current *Availability* is regarded. This enables a roller to acquire an additional task when it is nearly finished with the current work. The estimate is transmitted and subsequently the *Task Assignment* behavior receives a roller ID for the outstanding task from the paver. The winning roller acknowledges and activates one compaction behavior. Accordingly, either a *Track*, *Edge*, or *Seam* compaction is executed. If there exists no specific *Task*, the roller's *Iron* behavior is active.

8 Experiments

The presented approach was tested in a virtual road construction environment. Simulated tandem rollers compacted a road and assigned tasks based on the construction process and skills. The results were compared to recorded real road construction activities.

The control software was implemented using Finroc, a C++, Java based robot control framework [22]. The scenario was simulated using the Unreal Engine 4 (UE4). Sensors were modeled to behave similar to corresponding real systems [20]. A virtual model of the B10 highway, Germany, served as the test environment, where three BW 174 roller and a BF 800 C operated (Fig. 6). Real construction data was available for comparison.

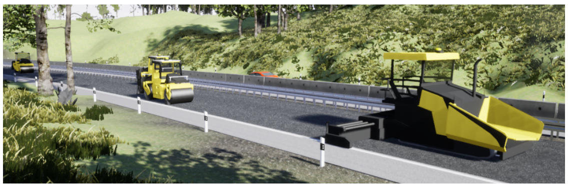

Figure 6. Road construction test on the simulated B10 highway, Germany.

The paved lane had a width of 7.5 m and length of approximately 1 km. An extract of the road as well as the asphalt cooling behavior is shown in Fig. 7. A comparison of human and robot trajectories can be seen in Fig. 8. In both trials, the lane was separated into 4 tracks. A human operator reversed after approximately 35 m, in contrast to the the autonomous systems with 25 m. The robots stayed strictly in the middle of the track and turned close to the paver. The human drivers navigated more imprecise inbetween the tracks. Additionally, the task separation differed. Real workers operated within different fields, where one roller compacted on all 4 tracks and the other roller stayed more behind. In contrast, the robots equally distributed the tracks of a field which results in a consistently distributed work-load.

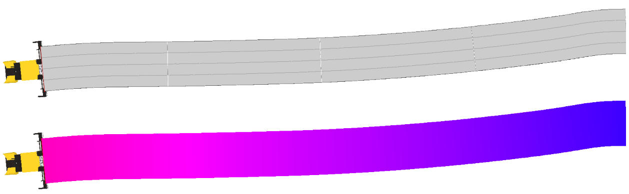

Figure 7. Extract of simulated lane of B10 highway with fields, and tracks. A temperature map shows asphalt cooling from hot (pink, 180 °C) to cold (blue, 80 °C).

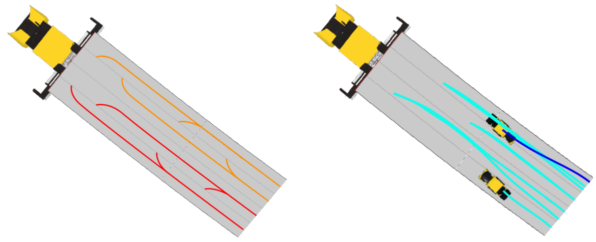

Figure 8. Simulated (orange, red) vs. human (turquoise, blue) trajectories in correlation to paved fields (gray).

9 Conclusion

This paper presented a novel approach for multi-robot collaboration in road construction. It provides an overview to the state of the art in autonomous road construction and multi-robot control. A formal road representation including layout, temperature, and compaction data is proposed. An inter-robot distributed BBS was used for task selection and assignment. Hereby, each roller competes for a task based on the suitability. The design compensates roller failures and distribute tasks accordingly. Finally, the system was tested in simulation and compared to real road construction data.

Future work targets an even more sophisticated road representation, which includes compaction errors as fractures, or bow waves. Additionally, the street model can be improved through considering more factors as different characteristics of mix proportions. Furthermore, varying asphalt supply as well as fluctuating weather conditions like wind or rain can be considered and impact on assignment and quality investigated. Finally, the concept should be tested using the real 5G-AMMCOA demonstrators.

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