Towards High-Quality Road Construction: Using Autonomous Tandem Rollers for Asphalt Compaction Optimization

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Abstract -

Autonomous road construction offers the possibility to improve the demanding and error-prone process of road compaction. Compaction results and surface coverage are optimized through the coordination of automated tandem rollers. This paper evaluates the impact of different road compaction strategies, ambient influences, and coordination errors on the resulting road. Thereby, suitable compaction parameters for track length, or number of rollers are determined. The concept has been validated in a simulated road construction environment. Additionally, real compaction tests have been performed using autonomous tandem rollers.

Keywords -

Off-road robotics; Behavior-based control; Automated road construction
Topics: (B-1), (B-2)

1 Introduction

Recent construction robotics proceeds towards the complete automation of demanding tasks as high-quality road construction [1, 2, 3, 4]. Thereby, the efficiency, safety, and quality of processes are increased while errors can be reduced. The area of road construction can profit from automation in particular because a fleet of machines has to be coordinated according to time restrictions, and spatial coverage to fulfill clearly defined tasks.

The automation of road work depends on the local construction and communication infrastructure and AI skills of construction robots. The project *Autonomous Mobile Machine Communication for Off-Road Applications* (5G-AMMCOA) funded by the German Federal Ministry of Education and Research (BMBF) targets key topics. The project demonstrators are two pivot-steered BOMAG tandem rollers BW 154 and BW 174 which have been equipped for autonomous operation.

This paper presents a set of improvements to increase the quality and efficiency of a road construction scenario. Furthermore, tests using different roller and road setups are done to conclude a setup for efficient road construction. Sect. 2 presents the state of the art of autonomous street construction. Sect. 3 gives an insight into the road model used for task distribution. Details on the road construction approach are provided in Sect. 4. Details on the robot control approach are stated in Sect. 5 including pivot point selection and multi-field compaction. In Sect. 6 handling of communication errors and task abortion criteria are presented. Finally, simulation and real-world experiments are shown (Sect. 7) followed by a summary and conclusion (Sect. 8).

2 Related Work

Current research aims to improve the quality of road construction processes. Cutting edge technologies as Blockchain and Machine Learning are deployed to improve road construction documentation and monitoring and prevent documentation frauds [5]. Also, road construction efficiency can be improved using the Internet of Things and Industry 4.0 techniques [6]. Additionally, the context-realistic training of construction site personnel as tandem roller operators using Virtual Reality and simulation is of importance to improve the quality [7].

Besides this, research targets the automation of the overall road construction process including the construction machinery as compactors. The automation of tandem rollers and the coordination with a paver was investigated by [3, 8]. Real-time path-planning and data exchange of compactors were investigated in the *SmartSite* project [2]. The follow-up project *Road Construction 4.0* aims to further improve the intelligent control of construction processes [9]. A behavior-based multi-robot coordination approach exploiting 5G-communication was presented in [4]. Additionally, assistance functionality for road construction tooling as automated edge cutting or autonomous collision prevention aid during reverse drive operations has been published in [10].

3 Road Model

The autonomous road construction approach involves a fleet of machines, as tandem rollers, feeders, pavers, and trucks. In the following, the tandem roller automation is targeted. Thereby, the tandem rollers share data with the paver to update a road model and coordinate themselves accordingly. The road model utilized by the robot control approach is described by [4]. The model considers a spatial description of the individual road segments as lanes, fields, tracks, seams, and edges.

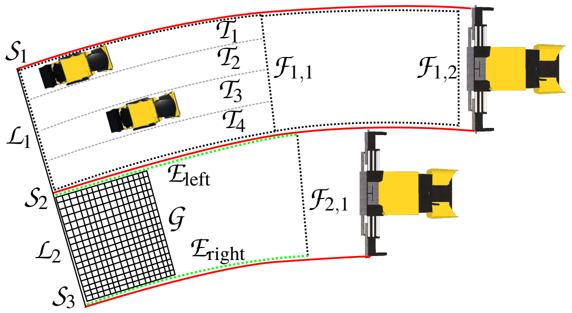


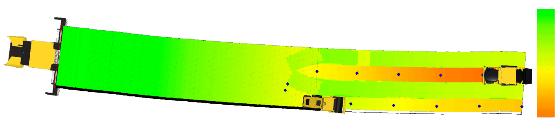
Figure 1. Road model for compaction planning. The road $\mathcal{R}$ has lanes $\mathcal{L}$, seams $\mathcal{S}$, fields $\mathcal{F}$, edges $\mathcal{E}$, grids $\mathcal{G}$, and tracks $\mathcal{T}$ [4, p. 955].

Further, the temperature of the road is considered since sufficient compaction is only possible within a given temperature span and therefore time duration.

The temperature visualization scheme is depicted in Fig. 2a. The road's amount of compaction is estimated through the number of transitions as shown in Fig. 2b. Resulting from current compaction status and temperature, the criticality for ongoing compaction can be determined. The compaction priority visualization can be seen in Fig. 2c. Areas with a low temperature and low compaction amount are visualized orange (high criticality) while hot areas or compacted areas are green (low criticality).

(a) Road temperature model (blue: cold asphalt ≤80 °C, pink: hot asphalt ≥160 °C).

(b) Compaction transition count (red: 0 transitions, green: ≥ 5 transistions)



(c) Compaction priority visualization (green: low priority 0, orange: high priority 1).

Figure 2. Road visualization.

4 Road Construction Approach

The tandem rollers use a distributed, behavior-based control approach [4]. Thereby, several extensions help to improve the compaction result as a more dedicated pivot point selection, multi-field compaction, and the consideration of overtaking maneuvers for a larger group of robots located within the same area.

4.1 Pivot point selection

During road construction, rollers move back and forth between two reversing points: one close to the paver, one further away. The reversing points in a track move forward, as the paver moves forward. The close reversing point will have approximately the same distance to the paver every time, assuming a constant temperature of the delivered material and a continuous material stream. Since the close reversing point is in very hot material, drivers usually make a small curve towards the end of the track. This leaves the wave of material in front of the drum in an angle to the next pass on this position, resulting in a better distribution of the material wave. Otherwise, the next pass could not distribute the material and a permanent wave in the road would be the result. The further reversing points can be chosen on the base of the track length.

Figure 3. Visualization of the reversing points close to the paver from a real world example.

Fig. 3 visualizes the close reversing points in a real world scenario. The building direction is from left to right. One can see how the close reversing points move from right to the left side as the roller changes the track to keep up with the paver. In the middle, there was a temporary paver stillstand due to a lack of material and the roller had

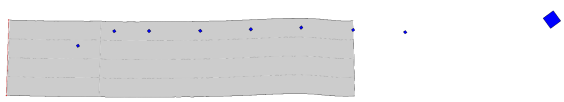


Figure 4. Spatial road visualization with pivot point (blue diamond), support points (track 1), and turn-in point (end point, track 2).

to pass some time resulting in an accumulation of close reversing points. After the stillstand the order in which the roller compacts the tracks change from right to left, to left to right. This is because the curvature of the road has changed and so did the cross slope. The roller always wants to start on the lower side of the road, building a foundation to compact against when moving up.

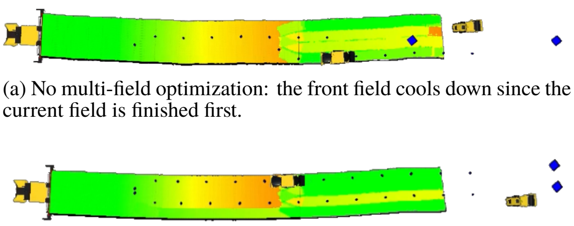
A lane, a set of support points, is generated to control the autonomous tandem roller. Since abrupt steering maneuvers damage the asphalt surface, sudden steerings have to be avoided. A smooth roller trajectory can be achieved on a track as depicted in Fig. 4. Therefore, a pivot point P_t as a turning point for moving to the next track has to be determined with a minimum distance of d_{min} to the end of the track. The value of d_{min} depends on the track width w_{track} and maximum allowed steering value $c_{\text{track, max}}$. The BW 154 has a drum width of $w_{\text{drum}} = 1.5\,\text{m}$ and a maximum curvature of

$$c_{BW154,\,max} = \frac{\tan\left(22°\right)}{1.35\,\text{m}} = 0.299\frac{1}{\text{m}} \qquad (1)$$

In the particular case follows $w_{\text{track}} = 1.3\,\text{m}$ (resulting from the track overlap), and $c_{max} = 0.1\,\frac{1}{\text{m}}$ to prevent sudden steering movements. In contrast to track switching, a turn in maneuver is executed at the front of each track.

4.2 Multi-field optimization

A suggested extension to the compaction process is multi-field optimization. The paver continuously lays out asphalt which can be structured into fields $\mathcal{F}$. For a slower compaction process resulting from a small number of rollers, it may also occur that the tracks $\mathcal{T}_{i+1,j}$ of the field $\mathcal{F}_{i+1}$ already cool down without being compacted accordingly. This results from rollers that are still occupied with the tracks $\mathcal{T}_{i,j}$ of the previous field $\mathcal{F}_i$ (Fig. 5a). Due to the low compaction amount of the field $\mathcal{F}_{i+1}$, a track of $\mathcal{F}_{i+1}$ may have a higher priority as the tracks of $\mathcal{F}_i$.



(a) No multi-field optimization: the front field cools down since the current field is finished first.

(b) Multi-field o ptimization, t he f ront fi eld is in cluded in to the compaction task.

Figure 5. Priority map visualization.

Multi-field o ptimization i s u sed t o a void insufficient compaction. Therefore, previous tracks $\mathcal{T}_{i,j}$ of the field $\mathcal{F}_i$ are included into the current compaction task (Fig. 5b). The compaction of track $\mathcal{T}_{i+1,j}$ also blocks $\mathcal{T}_{i,j}$ since the vehicle needs the track to adjust to the task. Accordingly, track $\mathcal{F}_{i,j}$ is only added to the task if its compaction is not finished yet. Furthermore, it is checked if the task is currently blocked by another roller. By that, it is avoided that the temperature of the unfinished field $\mathcal{F}_i$ drops below the minimum compaction temperature threshold while the rollers are compacting field $\mathcal{F}_{i+1}$. Further, the optimization prevents the adjustment of a task on any unfinished fields. Besides, it is more time-efficient since two tracks are compacted while only adjusting to the task once.

5 Robot Control

The following section proposes further navigation-based robot control add-ons. Such are overtaking maneuvers of other machines in blocked sections and an improved path planning for refueling of water and diesel.

5.1 Overtaking and local trajectory adaptation

An alternative pathway for traveling can be computed as follows (Alg. 1). Considering the field the roller is positioned on it is calculating a path to field $\mathcal{F}_{i-1}$ in front of the targeted field of the next task $\mathcal{F}_i$. Using the information saved in the road model a working begin $\mathcal{F}_w$ is defined. This is the first field of the road which is not finished due to its temperature and compaction value. A field is considered as finished if the temperature is too low or the compaction amount is sufficient. If a roller's position $\mathcal{F}_i$ is behind the working begin ($i < w$) it approaches $\mathcal{F}_w$ by following the points saved in the tracks $\mathcal{T}_{i+1,t-1}$ to $\mathcal{F}_{w-2,t-1}$ where t is the number of tracks.

Algorithm 1: Pseudo code for calculation of avoidance points.

```
if current field id < working begin then
    drive to working begin;
end
if task's field id - current field id > 2 then
    for i = task's field id; i < current field id; i++ do
        add avoidance points of field i to target points;
    end
end
add task points to target points;
```

It is ensured that the rollers are always taking a path in driving direction right on the road by taking the points of the track with the highest ID. The tracks are numbered from left to right and split a field into longitudinal overlapping paths, which are driven by the rollers. This ensures that the driven path is never blocked by a roller driving in the opposite direction.

Next, a path to the task's field has to be determined while not interfering with other rollers currently performing tasks. Usually, the number of rollers compacting a field at the same time is limited by the number of tracks. Additional rollers can be exploited by compacting fields further ahead. Since rollers are occupying the access route it is not necessarily possible to approach the task directly. Based on the number of fields between the current vehicle position and the target field of the task it can be determined if it is necessary to task evasive actions. If the number of fields between the current vehicle field $\mathcal{F}_i$ and the targeted field of the task $\mathcal{F}_k$ is smaller than two, the task can be approached directly. This is the case since task $\mathcal{T}_{k,j}$ is blocking all neighboring tracks, including the tracks on $\mathcal{F}_{i+1}$ which could be needed to approach the task. If the number of tracks between $\mathcal{F}_i$ and $\mathcal{F}_k$ is larger, other rollers may be occupying the tracks needed to approach the task directly. In this case, an avoidance lane is used which is located on the side of the road. In the case that a roller is required to take the avoidance lane, a request is sent to the paver. The paver is handling the assignment of this avoidance lane in the same way as the handling of the tracks. When performing an evasion maneuver a roller on-field $\mathcal{F}_i$ is aiming for the avoidance points of $\mathcal{F}_{i+1}$ and re-enters the road at $\mathcal{F}_{k-1}$. Afterward, the task can be directly approached.

5.2 Refueling

It is necessary to ensure the water and fuel supply of the rollers to achieve a successful compaction process. For this purpose, it is necessary to periodically send rollers to a refill station. Since the limiting factor of the compaction process is the slow speed of the paver, the refill process should not interrupt the compaction of the road. Typically at most one roller should perform a refill task at a time to secure ongoing compaction.

The refill task is assigned similarly to the standard compaction task. The fill levels of fuel and water of all rollers are monitored at the paver. The paver is creating and assigning the refill tasks based on the fill levels and two thresholds t_{refill} and t_{critical}. A roller is ready to be assigned a refill task in case the fill level is below t_{refill}. The t_{critical} threshold defines the fill level when the roller cannot perform any compaction tasks anymore before refueling. Therefore, each fill level is checked before assigning a new compaction task and refueling is started if at least one roller is fallen short of t_{refill}. Below a specific roller count, only one refill task can be performed at the same time. Accordingly, it is checked if a refill task is currently running. If this is the case, a second refuel task is not assigned and the assignment of the compaction tasks continues. In contrast, if no refill task is running, the roller with the lowest fill level starts refueling. The only case where more than one refill task can be performed similarly is the situation where multiple rollers fall below $t_{critical}$. In this case, the task is assigned independently of the currently running tasks, since the roller is incapable to perform other tasks anymore.

A roller with an assigned refill task follows the previously compacted road up to the road's begin using the points of $\mathcal{T}_{i-1,0}$ to $\mathcal{T}_{0,0}$. $\mathcal{T}_i$ denotes the field where the roller is currently placed on. The overtaking mechanism is used to avoid mutual interference at other field locations that have to be passed. A predefined path is driven which leads to the corresponding refill station after reaching the road's begin. Similarly, after refueling is finished, the roller navigates back to the entry point of the road $\mathcal{F}_w$.

6 Error Handling

A major issue in the communication between rollers and pavers is the handling of message loss and robot control failures. Those problems occur unintended and can consequently not be avoided. Typical situations are a data loss in the communication interface or safety-critical events as construction workers on the road which cause a safety stop of a roller. Therefore such events need to be explicitly regarded by the robot control to prevent a standstill of construction. This includes dynamically adding and removing rollers from the road works.

6.1 Communication failures

Rollers are continuously communicating with the paver and other rollers during the compaction process. Rollers are periodically sending the status of their currently assigned tasks. This is used for calculating new compaction tasks and monitor the state and finished tasks. Additionally, these updates are used as an acknowledgment mechanism to register whether an assignment message is received successfully. Besides, the messages are used to monitor if a roller is still active. If the paver's remote interface does not receive a status update of a roller for a set period t_{active} the roller is set to inactivity. Consequently, it is no longer part of the task assignment process. As soon as the roller is resuming the data transmission, it is reintroduced into the compaction process and can again receive tasks. Thus, t_{active} has to be chosen in a way that rollers can complete their current task before the threshold time is exceeded. A larger threshold is used for refill tasks (around 30 min) since they require a larger time duration due to the potentially large travel distance and the refilling time.

6.2 Task abortion criteria

Task abortion criteria are defined in addition to the communication failures. These should guarantee the revival of the process if an unforeseen event occurs as a roller does a safety stop. Even though the collision of the rollers is prevented by safety systems [11, 12], this does not resolve the problem that a path is not traversable. It is possible to define upper bounds which should not be exceeded since the time needed to perform a compaction task does not vary considerably. It can be estimated based on the track length and roller's velocity. Therefore, the task is aborted and the roller moves back to the starting point of the task if the execution of a compaction task exceeds this time. Consequently, a new task can be assigned.

7 Experiments

A series of simulated and real-world compaction tests have been performed to evaluate the road construction result. The robot control was implemented using Finroc, a C++/ Java-based framework for intelligent robot control [13]. For simulation, Unreal Engine 4 was used which interacts with the control framework using an interface plugin [14].

Simulated compactions trials were performed on a static test road and the virtual B10 highway, Germany. In a long-term test, a road segment of 800 m with a field width of 7.5 m was compacted. Thereby, the number of rollers and the general road layout data structure were adapted to evaluate the impact on the compaction result (Fig. 6). In a second series, both tandem rollers BW 154 and BW 174 of the 5G-AMMCOA project compacted a road on the ZAK test environment, Germany (Fig. 7). Approximately, 300 m road with a width of 6.5 m have been processed.

Figure 6. Simulated autonomous road compaction tests on the B10 highway using a varying number of rollers and field length.

Figure 7. Autonomous compaction trial on ZAK road using the tandem rollers BW 154 and BW 174.

7.1 Single field compaction

In the first series of experiments, the influence of different numbers of tracks and rollers on the compaction time of a single field is shown. For this, a set of rollers is compacting a static street segment with a length of 25 m. The tests aim to show the advantages of additional rollers on the compaction time of single fields (Table 1). The tests were performed simulating an ambient temperature of 20 °C, and a wind velocity of 5 m/s. To reach the targeted compaction value each track had to be driven two times. Driving a single track on this street approximately takes one minute plus some additional time for the task approach.

Using just one roller, it was not possible to completely compact fields with more than four tracks before the asphalt is cooled down below the stop temperature of 80 °C. Also, it can be seen that a third roller has no impact on the compaction of a field with four tracks since the field overlap limits the space to two rollers at the same time. On larger track numbers, the advantage of additional rollers can be seen on the compaction duration of the field.

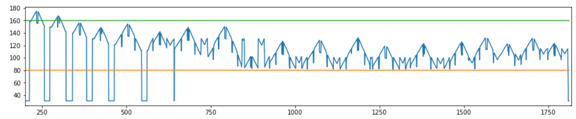
Table 1. Compaction duration for different track parametrization and varing roller counts.

# rollers	# tracks	duration [s]
1	4	630
2	4	360
3	4	360
1	5	–
2	5	540
3	5	350
1	6	–
2	6	600
3	6	420

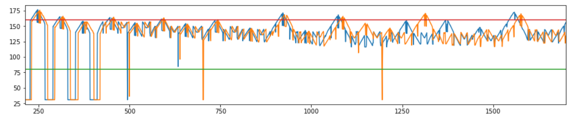
7.2 Simulated B10 compaction

In the simulation, a paver laid out asphalt on the virtual B10 highway. Hereby, each test run was repeated with different test parameters as the number of rollers, compaction field length, and ambient conditions. Each test was running for approximately 30 min creating a road segment of 250 m length. A base course was paved which had a width of 7.5 m resulting in four tracks. The ambient conditions are an initial temperature of 20°C and wind velocity 5 m/s.

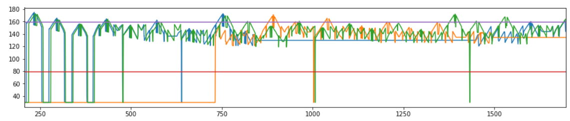
Number of Rollers In the first tests a fixed field length of 25 m is used and the number of rollers is varied. Thereby, it was not possible to sufficiently compact the road using a single roller only since the maximum area the roller can compact in a given time is lower than the area created by the paver. Therefore, after successfully compacting the first fields, the single roller is not able to finish the later fields before cooling off. Using two or three rollers, it



(a) Temperature measurements single roller trajectory over time.

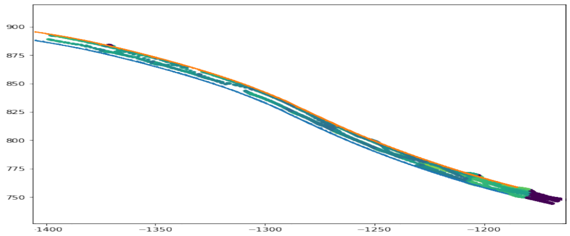


(b) Temperature measurements dual roller compaction over time.

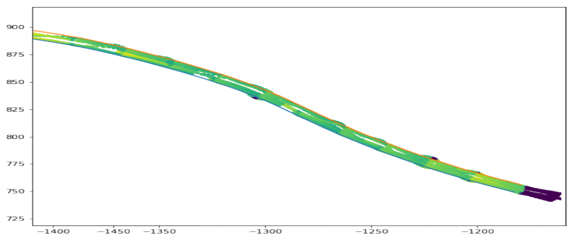


(c) Temperature measurements three roller compaction over time.

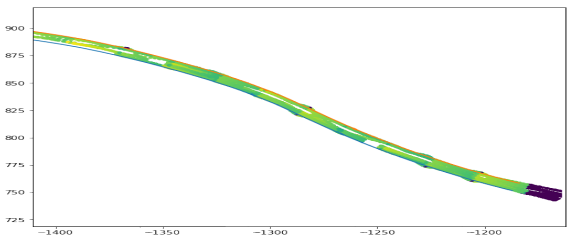
Figure 8. Compaction temperature for the tests with one (a), two (b), and three (c) rollers. The top straight line represents the start temperature (160 °C) the bottom line the stop temperature (80 °C).



(a) Temperature-trajectory plot single roller test.



(b) Temperature-trajectory plot dual roller test.



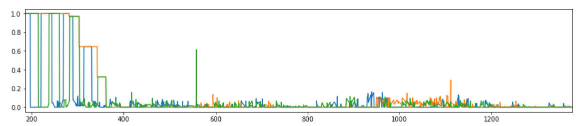
(c) Temperature-trajectory plot three roller test.

Figure 9. Temperature plot according to the roller trajectories. Light green depicts a high temperature (160 °C), purple is below the stop temperature (80 °C).

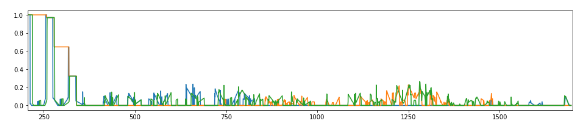
was possible to compact the road within the temperature windows. However, it should be mentioned, that due to the short test duration, no refills had to be performed. Upcoming refill tasks might negatively affect dual roller performance because the scenario changes to a single roller case in-between. Due to this, the deployment of a third roller is recommended in this scenario.

Fig. 8 depicts the surface temperatures measured by the rollers. It can be seen, that in the single roller case, the roller operates most of the time close to the lower compaction threshold temperature of 80 °C. After a while, the roller always compacts tracks which are close to the stop temperature, since they are the most urgent ones. Fig. 9 plots the temperature data against the spatial position of each roller. It can be seen that the overall track temperature is colder (in the visualization more bluish) than in the multi-roller tests. Also, at a later position on the road, only two of four tracks are compacted. In the temperature visualization of multiple roller tests (Fig. 8b-c), it can be seen that the track's temperature is usually close to the start temperature (160 °C). This provides some buffer time for unforeseen delays. Additionally, it can be observed, that in the three roller tests idle times appear in the temperature plot since no task is valid at the moment. In such a situation, the roller has the default behavior to iron a part of the road until a new task becomes available. Temperature data is measured at the kinematic center of the roller. Therefore, some gaps appear in the multi roller spatial plot. This results from the length and width of the roller.

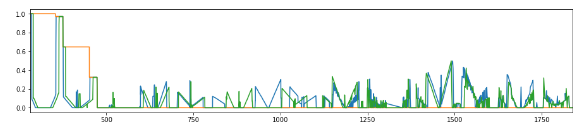
Field length In another trial, the impact of the field length is considered. In addition to the standard field length of 25 m, two additional runs are performed using field lengths of 12.5 m, and 50 m. In general, the desired compaction was achieved in all three road setups.



(a) Compaction criticality for a field length of 12.5 m

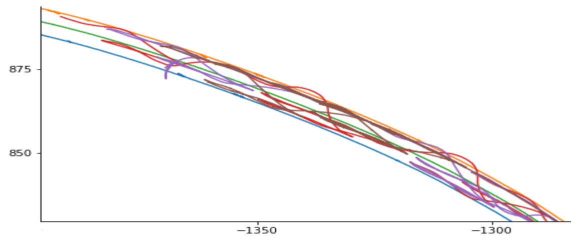


(b) Compaction criticality for a field length of 25.0 m

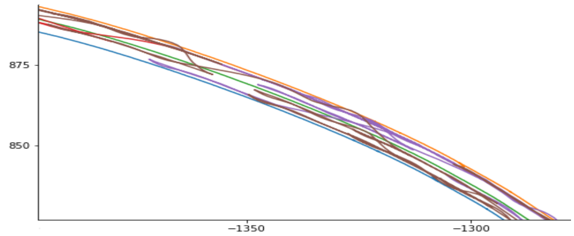


(c) Compaction criticality for a field length of 50.0 m

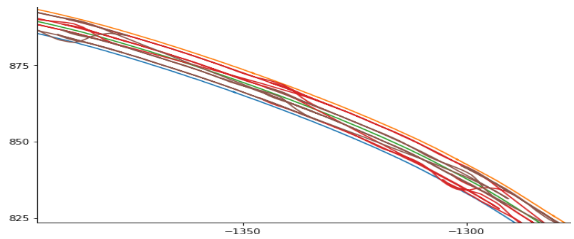
Figure 10. Critically of the for a field length of 12.5 m (a), 25 m (b) and 50 m (c)



(a) Trajectories for a field length 12.5 m



(b) Trajectories for a field length 25.0 m



(c) Trajectories for a field length 50.0 m

Figure 11. Driven trajectories for different field length.

Anyways, the different layouts had various advantages and disadvantages.

In the tests with a short field length, the approach seemed to be much more reactive. The tracks are finished faster and are mostly compacted at high temperatures. This can be seen in the plots of the track criticality value of the road. The critical value is a combination of the temperature and the current compaction, indicating how critical the compaction of a track is at the moment (see Fig. 10). A roller has to wait shorter for a smaller field length to start the compaction than for a larger field length. A major issue is the approach of a task start destination. On one side, the number of task approaches is doubled, since the number of tracks is double. However, the main issue with the task approach is, that the maneuvering needs space in front of the track which should be compacted Fig. 11. The needed space behind the field is larger than the field length of 12.5 m. By that, when approaching a task at field $\mathcal{F}_i$, both the corresponding tracks of $\mathcal{F}_{i-1}$ and $\mathcal{F}_{i-2}$ have to be blocked, while the tests with higher field length only require to block the tracks of $\mathcal{F}_{i-1}$. Driven trajectories are easier to perform using the 50 m fields because less steering are needed Fig. 11. In contrast, the critically of the compacted asphalt is higher in these tests (Fig. 10c) due to the increased time to travel to a track. This is the case due to the larger temperature differences between the start and the end of the field. It also leads to a later beginning of the compaction, since the compaction is started after the average temperature of the track is below the start temperature of 160°C. Finally, another disadvantage is that the number of tracks available for compaction is low and that additional rollers are not exploited. In long term tests a field length of 25 m has achieved the best results.

7.3 Ambient Influences

The time available to compact a field is strongly dependent on the ambient temperature and wind velocity. For simulation, an estimation of the temperature is done. In the real scenario, the temperature is updated using the measurements of the rollers in addition to the model. To show the importance of ambient influences, the available simulated compaction time is shown for different conditions (Table 2).

Table 2. Compaction time based on ambient influences.

temperature [°C]	wind velocity [m/s]	duration [s]
10	5	580
20	5	630
30	5	690
20	10	400
20	20	240

7.4 Real-world ZAK compaction

Finally, tests on the real machine were performed. A single roller was compacting a road consisting of one field (Fig. 12) using the best performing setup from the simulation tests. In general, the roller was able to compact the field as expected and all timing and temperature constrains were fulfilled. However, the accuracy of the trajectories is lower than in simulation and has to be regarded more careful in future. Also, the steering actions are often too large which is not desired when driving on hot asphalt.

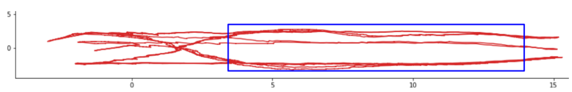


Figure 12. Track compaction trajectory of the ZAK test using BW 174 on a single track.

8 Conclusion

This paper presented different extensions to improve the results of autonomous road compaction, regarding the road mode, robot control optimization, and error handling. The impact of different parameters as number of rollers, field length, and ambient conditions was evaluated within a series of autonomous compaction trials in simulation and real world. The number of required number of rollers and the impact of different field length have been discussed.

Future work aims to consider trucks properties into the compaction planning. So, varying asphalt installation temperatures resulting from transport are included into planning. Also, real-world autonomous compaction tests on hot asphalt are targeted and the impact on sensor quality and the control behavior further examined.

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