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CONCEPTUAL DESIGN AND EVALUATION OF SENSOR TECHNOLOGY FOR AUTOMATIC UNCOUPLING OF RAILROAD WAGONS

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ABSTRACT

Across Europe the obsolete screw-couplers, which are currently used to connect cargo train wagons to each other, are to be replaced by a new type, the so-called Digital Automatic Coupler (DAC). This new coupling type automates the coupling between two wagons, but, depending on the final implementation, not the decoupling, which still has to be done manually. As such, to make use of the full potential of this new technology and to make a step towards a fully autonomous rail system, the decoupling is to be automated as well within marshalling yards. The purpose of this paper is to develop and evaluate a sensor system for a track-side device that can autonomously perform this task.

Concepts for such decoupling devices have been around for decades, both for centre-buffer-couplings and the obsolete screw-coupler, yet only few of these were ever tested and none found any commercial adoption. This seems to be due to the difficulty of developing such a technical solution and the cost of implementing it.

Therefore, a new sensor system is to be developed, which can perform reliably even in the harsh environments of marshalling yards. The system is to identify and localise couplings which are to be separated. Three different concepts to achieve this are designed and evaluated. The best concepts regarding the results of this evaluation are a distance measurement concept, using laser and radar distance sensors, and a wagon localisation concept, using axle counters. The concept utilising the distance measurement is then built and tested under realistic conditions in a small marshalling yard on a train equipped with DACs.

Using the recorded data from these tests, methods for signal processing are tested and compared to localise the couplings in the datasets. The methods best suited for this regarding the results of this evaluation are a histogram analysis and a cross correlation. An algorithm combining these two methods is developed, which allows for reliable localisation of the couplings on a passing train.

Due to issues with the used sensors the accuracy of this localisation is severely lacking. While the concept of the distance measurement and the algorithm both work well, the used hardware in its used configuration proved to have severe issues. The laser sensors are unreliable in the harsh conditions of the marshalling yard, while the radar sensors are not dynamic enough. However, these issues seem to be resolvable with more effort or using different hardware. Regardless, the results of this paper pose an excellent basis for the future development of this system, which involves improving the sensor system with the experiences gathered up to now and developing the actuator system for interacting with the couplings.

1. INTRODUCTION

In order to combat climate change and to improve and diversify transportation across Europe, the EU has started immense initiatives to help the railway industry catch up to other modes of transportation. In 2011 the European Commission set the goal of shifting at least 30% of all road freight which travels further than 300 km to other, more environmentally friendly modes of transport, such as rail. The Shift2Rail and the European Rail Joint Undertaking initiatives both aim to drive innovation in the rail sector and to make transportation by train a more attractive alternative to trucks or planes.

A total of approximately 105 million tons of freight were transported in freight wagons on Austrian rails in 2018 (Karner *et al.*, 2018). These wagons are typically connected to each other via outdated screw couplers, which require a lot of manual effort to couple and uncouple. To reduce this effort and thereby reduce freight train turnaround times and the risk of accidents for railroad employees, these obsolete couplers shall be replaced with a newer type. This new type is the so called Digital Automatic Coupler (DAC). The aim of these new DACs is to improve the general efficiency of cargo transportation by rail and to act as an enabler for new technologies. Preliminary work necessary for such a monumental task, such as first studies, tests and requirement engineering, was performed by the DAC4EU project, and is being continued as part of the European Rail Joint Undertaking.

With the changeover to a new type of coupler, it makes sense not only to upgrade wagons and make them smarter, but also to optimize parts of marshalling yards and the shunting processes. This optimization may be necessary for rail freight to remain relevant in the future. While road transport in particular is becoming increasingly attractive thanks to new innovations, rail freight is lagging behind. New technologies are needed, especially in train formation facilities, to keep rail competitive (Pelz, 2018).

As part of this change, not only should the work be made easier for rail employees, but if possible, they should no longer enter any hazardous areas at all during coupling and uncoupling. To this end, a system is to be developed that enables the new type of coupling to be uncoupled autonomously. The aim of this paper is to develop and evaluate a sensor system for such a system.

1.1. REQUIREMENTS

A sensor system for a mechatronic system that can autonomously interact with the decoupling mechanism of the correct coupling is to be developed. Therefore, the system has to be able to detect which coupling is to be separated and where the decoupling mechanism for said coupling is located.

The system should be able to operate at hump yards under the same conditions as a human being. This means that the system can be used at temperatures of -20°C..+50°C, in all weather conditions, except for hail and snow, at twilight, in strong sunshine and at night, under the influence of dust, and the like. A hump yard is basically divided into four parts: Entry group, hump, classification group and exit group. The system should be at the hump, or, if necessary, just before it, in order to separate the couplings at the right location.

The new type of coupling, known as the Scharfenberg coupling, is uncoupled with the operation of a simple cable and automatically couples on impact with a second coupling. This system is currently in use in Europe for passenger trains. It is to be expanded upon, allowing the couplers to automatically couple and uncouple pneumatic lines, power cables and data cables, hence its new designation “Digital Automatic Coupling (DAC)”, as it is seen in Figure 1. The decoupling mechanism, which is currently just the red handle on the coupler head, is to be moved to the side of the wagon, so that personnel can interact with it without stepping between wagons.

Figure 1: Photo of two coupled DACs by VOITH (Voith GmbH & Co. KGaA, 2022).

Research Question

Due to the mentioned issues facing railroad operation the following research question therefore presents itself: Which sensor system is best suited to identify DACs that are to be separated and to locate their decoupling mechanism under extreme environmental conditions?

2. LITERATURE RESEARCH

For the literature research, the following directories were used:

- The Eurailpress Archive, as one of the largest publishers of railway related articles, news and trends.
- The IEEE Xplore database, as it is a large publisher of any scientific engineering work.
- The ScienceDirect database, as a large publisher of any scientific work.
- The Google Patents database for any non-scientific work done in this field.

A very similar paper on automatic uncoupling has already been written in (Zellner, 2019), but for the screw couplers currently in use. However, the differences between the two types of couplings are so extreme that the former work cannot be applied to the new type of coupling. Also, the literature found is mainly for the screw coupling, but some patents intended for automatic couplings have also been analysed (Zellner, 2019).

Of the patents found, most simply place a 6-Axis robot next to the track, usually on some sort of linear axis to move along with the train, to interact with the couplings. They also mention a sensor system to localise the couplings, yet never describe it in greater detail. Such systems were described for different types of couplers, including the SA-3, the central automatic coupler, and the Janney coupler (Bruns *et al.*, 1990; Cappelletti and Zakaria, 1996; Wadim Borissowitsch Swerdlow, Sabit Gaidanievich Akmalov, and Grigory Yulievich Irger, 2012; Shao Zhiguo *et al.*, 2019). Of the found patents only one seems to have been developed into a prototype, the development of which into a full product was never continued (Bruns *et al.*, 1990; Rake, Schanhaeusser and Enning, 1993). No system for automatic decoupling of wagons seems to be in widespread use in the world.

Apart from patents, no scientific papers or non-scientific articles could be found that specifically address this topic. The main focus of research and development currently seems to be on the automation of shunting locomotives. This seems to be because they are often a bottleneck in the shunting process and seem to have the greatest potential for savings (Knapmöller and Pritsching, 2018; Nasonov *et al.*, 2018; Redaktion, 2020, 2021; Stadlmann *et al.*, 2021; Ramírez *et al.*, 2022).

3. APPROACH

The approach to this issue can be split into two parts: The development of a coupling detection system and the development of an algorithm to evaluate the data recorded by the sensors.

3.1. COUPLING DETECTION SYSTEM

The sensor system must perform two tasks: On the one hand, the localisation of the decoupling mechanism or the coupling; on the other hand, the coupling identification to determine whether the coupling should be disconnected at all.

Coupling identification is relatively simple. If the couplers can be reliably located, then the system can count the passing couplers and can then, for example, disconnect the fifth coupler of the train by command from a control centre. This assumes that there is a connection to some sort of control centre, but this must be in place anyway to allow the system to be autonomous. The system must either receive information about which train is approaching and which couplers of it are to be released, or simply the information that, for example, the third, fifth and eighth couplers are to be released. Alternatively, a camera system can be used to evaluate the wagon labelling, as described in (Zhang, Bahrami and Liu, 2021). The wagon numbers and the split list can then be used to determine the couplings to be separated.

Localizing the uncoupling mechanism is more difficult than coupling identification, as it is not clear yet what the mechanism will look like. Instead, the couplings themselves will be localized, since it can be assumed that the decoupling mechanism will be in a fixed position relative to the coupling. A sensor system must be developed for this purpose.

Sensor Technologies

This chapter aims to summarise what sensor technologies can be used in which way to localise the couplings.

Optical Measurement
Optical measurements in this context include sensors that use optical technologies to find recognisable characteristics of the coupler heads. This includes devices such as traditional cameras, depth cameras and light section. The disadvantages of these technologies include a lack of reliability under harsher conditions and an extreme processing power requirement.

Distance Measurement

Due to the large number of variants of wagons, it is difficult to identify or locate them correctly, but the couplers on each wagon are identical in construction, except for small, manufacturer-specific details. They are always centred on the track axis and therefore represent a prominent gap when viewed from outside the track. Therefore, it should be feasible to recognize the coupler from a fixed location next to the track by measuring the distance to a running train. This approach allows the usage of many different methods, from single point measurements to single layer measurements to full 3D measurements, using different technologies, like laser, radar or ultrasound.

Wagon Localisation

Instead of localising the couplers directly, it may be easier to localise the wagons and to infer the couplers' location indirectly from that. The wagons are symmetrical across their middle, while the coupler heads are in a defined distance to each other. Using these geometrical relations, the coupler position can be calculated if the wagon centre is located. To locate the wagons a sensor to detect the wheels of a train, called axle counters, could be used, since the wheels are also located symmetrical to the centre of the wagon. Alternatively, a system using RFID tags could be used, if such tags or readers are mounted on the wagons, as they can be localised with relative ease.

Speed Measurement

If the system is to be used on moving trains, measuring their speed is unavoidable, as it must be known to interact with a moving wagon. For this purpose, several technologies are feasible, including axle counters, radar, or optical sensors.

Evaluation of Concepts and Sensors

In this chapter, the technologies and concepts described are qualitatively compared with each other in order to design a single concept based on this comparison that can also be tested. The different technologies of each concept are compared to each other, while the concepts themselves are compared to each other. For this purpose, characteristics like accuracy, robustness, sampling frequency, etc. are considered. These are valued from 1 to 4, with 4 being the best, then summed up and this sum divided by the maximum available points. All the characteristics are weighted equally, as they are all equally important for the successful implementation of this system. This resulting ratio is then entered in the "Value" cells, meaning that the closer any technology or concept is to 1 the better it is.

Optical Measurement			
	Cameras	Depth Cameras	Light Section
Accuracy	2	2	4
Robustness	1	3	3
Sampling Frequency	2	2	3
Availability	4	3	3
Evaluation Options	4	4	3
Evaluation Effort	1	1	4
Sum	14	15	20
Value	0.58	0.63	0.83

Distance Measurement			
	Laser	Radar	Ultrasound
Accuracy	4	3	3
Robustness	1	4	3
Sampling Frequency	4	3	1
Availability	4	1	3
Evaluation Options	4	4	4
Evaluation Effort	4	4	4
Sum	21	19	18
Value	0.88	0.79	0.75

Table 1 and 2: Evaluation of the technologies for the optical and distance measurement.

Wagon Localisation		
	Axle Counter	RFID
Accuracy	3	3
Robustness	4	1
Sampling Frequency	1	1
Availability	4	3
Evaluation Options	4	4
Evaluation Effort	4	4
Sum	20	16
Value	0.83	0.67

Table 3: Evaluation of the technologies for the wagon localisation.

Speed Measurement			
	Axle Counter	Radar	Optical Systems
Accuracy	2	2	4
Robustness	1	3	3
Sampling Frequency	2	2	3
Availability	4	3	3
Evaluation Options	4	4	3
Evaluation Effort	1	1	4
Sum	14	15	20
Value	0.58	0.63	0.83

Table 4: Evaluation of the technologies for the speed measurement.

Concepts for the Coupling Localisation			
	Optical Measurement	Distance Measurement	Wagon Localisation
Accuracy	3	3	2
Robustness	1	4	3
Evaluation Effort	1	3	4
Sum	5	10	9
Value	0.42	0.83	0.75

Table 5: Evaluation of the different methods for the coupling localisation.

The result of this analysis is that the optical measurement seems poorly suited to this task, while both the distance measurement and the wagon localisation are promising approaches. This matches expectations, as robustness and evaluation effort were both intuitively low for the optical measurement even before this comparison, while the other measurements seemed to be promising.

Selection and Construction of Sensor System

Based on the results of the analysis a sensor system is selected and constructed for field tests. The best system would be a combination of the distance measurement, speed measurement and wagon localisation; However, for the purpose of field tests, the wagon localisation is too difficult to implement. Mounting axle counters on the rails or RFID tags on wagons is not an option for preliminary tests, as operators generally do not allow interfering with the infrastructure in such a way for simple tests.

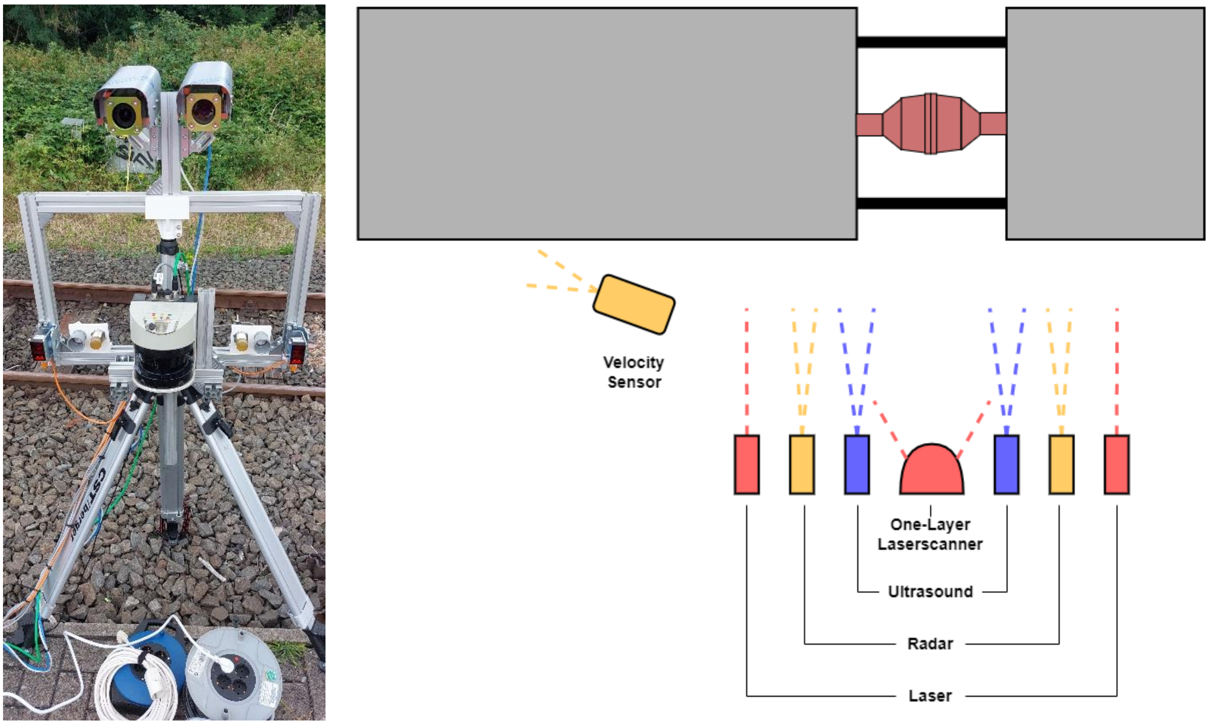

Figure 2: Photo of the field test equipment and diagram depicting its placement.

Figure 2 shows a photo of the sensor construct and a diagram depicting how it is placed in relation to the tracks and wagons. It consists of two laser, radar, and ultrasound distance sensors, one one-layer laserscanner and one radar speed sensor. Two cameras are also mounted on top, but these are only for supervision purposes and are not used to localise the couplings. This setup is mounted on a simple tripod, making it highly mobile.

3.2. LOCALISATION ALGORITHM

To actually localise the couplers the data recorded by the sensors has to be processed and analysed. For this purpose, several different approaches were tested, including a cross-correlation, a spectral analysis and a histogram analysis. The data for testing these algorithms was gathered on the DAC4EU demonstrator train, as seen in Figure 3, using the described setup.

Figure 3: Photo of the DAC demonstrator train.

Figure 3 depicts the demonstrator train on which the setup was tested. It consists of 18 wagons of different variations, with DAC prototypes of both VOITH and Dellner.

Cross-Correlation

The cross-correlation is used in signal analysis to describe the similarity of two signals. For use in coupling localisation, this means that cross-correlation can be used if the signal that a sensor measures at the coupling is always similar. An analysis of the raw data shows that this is the case, however, many similar signals also seem to occur when measuring the wagons.

To perform this cross-correlation the raw data is filtered, and a signal of a coupler selected as a template. This template is then cross-correlated with the full signal. This is done for every distance sensor technology, i.e., laser, radar, ultrasound and the one-layer laserscanner.

Spectral Analysis

Rather than using the signals in the time domain, a transformation into the frequency domain to analyse spectral characteristics could be beneficial. The aim here is finding characteristics unique to a coupler signal. For this purpose, the Fourier transformation, the power density spectrum, spectrograms and coherence are analysed.

Histogram Analysis

Another option to analyse the data is to look at the distribution of the sensor measurements using a histogram analysis. Each measurement of a certain time range is assigned to a bin containing all values in a certain range, then the bin sizes between the signal and the template are compared.

4. RESULTS

The results of the tested setup and algorithms are very promising. Of the tested technologies, the laser and ultrasound distance sensors unfortunately proved to be unsuitable for this application, as the ultrasound sensors were too slow and the laser sensors were too easily affected by adverse conditions. However, the radar distance sensor and the one-layer laserscanner proved to be usable for the application. Of the tested algorithms, only the spectral analysis yielded no usable results, while the cross-correlation and the histogram analysis are both very promising. While both the cross-correlation and the histogram analysis occasionally detect false positives, a combination of the results of the two allowed a coupling localisation without any false positives.

The algorithm therefore works as follows: The cross-correlation and the histogram analysis each analyse the raw sensor signal separately, by comparing it to the template of the coupler. Peaks in the cross-correlation and valleys in the histogram analysis signify similarities to this template. These are extracted and, if a valley of the histogram analysis and a peak of the cross-correlation are close together, the average between the two is calculated and used as the calculated coupler location.

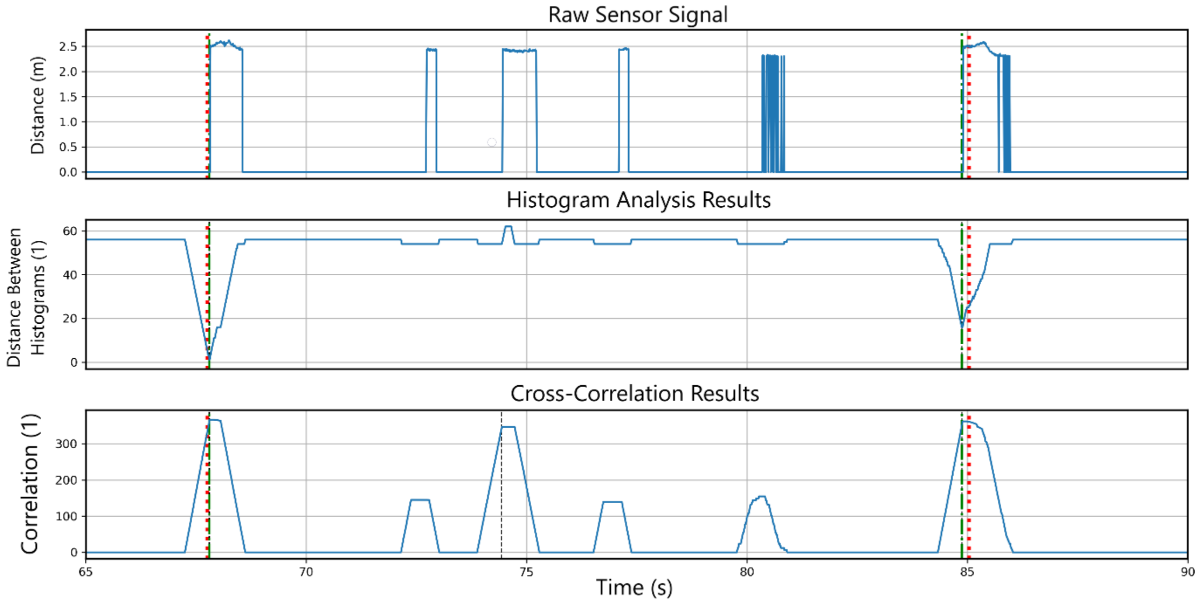

Figure 4: Diagram of the results of the coupling localisation algorithm.

Figure 4 depicts the results of the coupling localisation algorithm. The red dotted lines indicate the actual position of the couplings, the black dashed line indicates the position calculated by the histogram analysis and the cross-correlation in their respective diagrams, and the green dash-dotted line indicates the position calculated by the algorithm, combining the histogram analysis and the cross-correlation. The black dashed lines are usually at the same position as the green line, indicating that the results of each individual method are extremely close to each other. This diagram shows how using only the cross correlation would return a false positive at around 75 s, where it would confuse a part of the wagon as a coupler. Using only the histogram analysis would yield similar results in other situations.

The spatial accuracy of the localisation, in other words how close the localised coupler is to the real one, is hampered by the used sensor and its configuration. With the tested configurations an average accuracy of about 30 cm could be achieved, which is likely to be too inaccurate for further use. Additionally, the radar distance sensor would occasionally fail to measure the distance all the way to the coupler, meaning the raw data would look like just another part of a wagon, resulting in a false negative. This also seems to be due to the configuration of the sensor, according to the manufacturer.

5. CONCLUSION

The aim of this work was to develop, evaluate and test a sensor system to identify and localize novel couplers of freight cars in order to uncouple them via an autonomous mechanism in the future. By switching to this new type of coupling and automating this cumbersome manual process, the railroad should be able to better realize its potential as an alternative to road freight transportation while improving work quality and safety for shunting employees.

Various concepts have been developed and evaluated for this coupling localization, with a robust method emerging that can locate couplings using only a simple distance measurement. Various applicable technologies have also been evaluated for the methods, with radar distance sensors emerging as the best option for this purpose. The developed concept was then tested under realistic conditions on a demonstrator train, yielding valuable data. This data was then processed with the presented signal processing methods, the results of which are already good, with room for improvement.

The setup and the methods presented in this paper are a promising first iteration in solving the presented problem. With a few refinements and further tests this approach can be developed into an autonomous system usable in a real marshalling yard. Further steps are therefore improving the sensor setup, e.g., by adding more distance sensors in different positions and angles, testing the used sensors with different configurations, and developing a mechanism to interact with the decoupling mechanism, once its design is defined.

Possible issues with the future development could be, amongst other things, finding opportunities to test further iterations of this system, as there is currently only one test train in use across Europe. Another issue is confirming and improving the reliability of the system, as there are many different scenarios and conditions that could affect it adversely, and testing or simulating all of these conditions is impossible. It is also unclear currently what the DAC is ultimately going to look like, and as such it is difficult to say at this stage how easy it would be to automate a mechanical device to interact with the coupler heads, which is the end goal of this system.

REFERENCES

Bruns, M. *et al.* (1990) ‘Einrichtung zum vollautomatischen Trennen von Güterwagen mit automatischen Kupplungen’. German.

Cappelletti, J. and Zakaria, S. (1996) ‘Einrichtung zum vollautomatischen Trennen von Güterwagen mit automatischen Kupplungen’. German.

Karner, T. *et al.* (2018) ‘Verkehrsstatistik 2018’. STATISTIK AUSTRIA.

Knapmöller, A. and Pritsching, C. (2018) ‘Pilotprojekt automatisiertes Rangieren - Die Zukunft des Rangierens’, *Signal+Draht*, 110(6), pp. 23–27.

Nasonov, G. *et al.* (2018) ‘Erfahrungen bei dem Einsatz des Systems MSR32 auf dem Rangierbahnhof Luzhskaya’, *Signal+Draht*, 110(11), p. 65.

Pelz, M. (2018) ‘Der Einfluss innovativer Cargo-Lösungen auf die Automatisierung des Bahnbetriebs’, *Signal+Draht*, 110(6), pp. 15–22.

Rake, H., Schanhaeusser, W. and Enning, M. (1993) ‘Automatisierung von Ablaufanlagen mit dem Entkupplungsroboter’, *Eisenbahntechnische Rundschau*, (04), pp. 249–254.

Ramírez, R.C. *et al.* (2022) ‘Freight Train in the Age of Self-Driving Vehicles. A Taxonomy Review’, *IEEE Access*, 10, pp. 9750–9762. Available at: https://doi.org/10.1109/ACCESS.2022.3144602.

Redaktion (2020) ‘Niederlande: ProRail, Lineas und Alstom testen automatisches Rangieren nach GoA4’, *Signal+Draht*, 112(7+8), p. 65.

Redaktion (2021) ‘Fully automatic GoA4 shunting locomotive: DB Cargo chooses Railergy for development and approval’, *Signal+Draht*, 113(11), pp. 64–65.

Shao Zhiguo *et al.* (2019) ‘A kind of suspension type railway freight automatic decoupling device, system and method’. Chinese.

Stadlmann, B. *et al.* (2021) ‘autoSHUNTING – Beispiel einer automatischen Wagenbeistellung’, in U. Brunner et al. (eds) *Jahrbuch der Logistikforschung - Innovative Anwendungen, Konzepte & Technologien*. Linz: Trauner Verlag (Schriftenreihe Logistikforschung, 3).

Voith GmbH & Co. KGaA (2022) ‘Digitale Automatische Kupplung’. Available at: https://voith.com/corp-de/verbindungskomponenten-und-kupplungen/zugkupplungen/digitale-automatische-kupplung.html (Accessed: 9 August 2022).

Wadim Borissowitsch Swerdlow, Sabit Gaidanievich Akmalov, and Grigory Yulievich Irger (2012) ‘Automatic system to uncouple cars on hump yard’. Russian.

Zellner, C. (2019) *Automatische Trennvorrichtung für Güterwagen*. Dissertation TU Wien.

Zhang, R., Bahrami, Z. and Liu, Z. (2021) ‘An Effective Method for Automated Railcar Number Detection and Recognition Based on Deep Learning’, in *2021 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE)*, pp. 1–6. Available at: https://doi.org/10.1109/CCECE53047.2021.9569135.