Increasing Safety and Efficiency of Railway Transport: A Biologically Inspired New Approach

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Abstract—Current traffic control in rail transportation is heavily infrastructure-based and therefore very costly. This work proposes a biologically inspired solution for the coordination of trains in dense railway networks, avoiding collisions with considerably higher cost efficiency than the state of the art solutions. This solution does not require track mounted infrastructure, instead it relies on the continuous cooperation between trains. Inspired by self-organizing biological systems, two simple algorithms are proposed for managing points of conflict or switches where the right of way or priority of trains has to be carefully handled. The first-level algorithm avoids local collisions by the exchange of status information through beacons. The second-level algorithm uses one-hop or multi-hop communication to share the network status among trains and coordinates the trains in possible conflict zones around switches or in shunting yards. The proposed solution can decrease the signalling cost of railway transport substantially. This efficient approach can significantly reduce the probability of accidents caused by human and hardware errors. In addition, the proposed approach can lead to significant time and energy savings in railway transport. The biologically inspired solution proposed in this paper might lead to a paradigm shift in the signalling system used in rail transportation.

I. INTRODUCTION

Rail transport is a very energy efficient means of freight transport. Compared to road transport using trucks, it consumes substantially less energy [1]. Because of its environmental benefits, there is a current push for the use of trains for freight transport in many countries. The main disadvantages of train transport, however, are the high cost of deployment and maintenance of the infrastructure.

An important portion of the infrastructure budget is used to build the signalling system: in Europe, for instance, it comprises up to 10% of the infrastructure expenses [2]. Railway signalling provides traffic control to trains and thereby helps to prevent accidents.

The state of the art railway safety system, known as signalling, is based on a technology which goes back to the 19th century. The principle of signalling is fairly simple: trains are given permission by means of signals to move into the blocks, track sections, in which the railway lines are divided. The signalling system ensures that two trains are not allowed to occupy the same block at the same time. While in the early 19th century signals were given by railway officers by means of hand signals, this very primitive signalling system

has gradually evolved to more advanced signalling systems such as the Communication-Based Train Control (CBTC) [3] where trains communicate with track equipment by means of radio signals.

All these signalling systems have the common need for track equipment for every block. Heavy use of infrastructure is the underlying reason behind the high cost of safety in rail transport. Paradoxically, the shorter the blocks, the more efficient is the railway traffic, since the transport throughput is higher, but at the same time the more expensive is the signalling installation and maintenance.

Thus, it can be concluded that the state of the art infrastructure-based safety systems do not provide a cost-effective solution. The more kilometers of railway, the higher would be the cost of safety. The higher the traffic volume the lines should handle, the higher is the cost of safety. Moreover, despite the existence of this cost-intensive system, due to its complexity and huge amount of hardware required, the probability of failure is not negligible. A statistic from U.K reports that in the last years an average of one train a day failed to stop at lights, Signals passed at danger (SPAs). As a consequence, 21% of the SPAs posed a threat for accidents [4]. In the last years, train accidents have cost more than 3 billion dollars in the USA alone [5]. Besides accidents, signalling failure leads to delay. Railtrack plc., the UK railway operator, owing 32000 km of track and 2500 stations, reported that during 1999-2000, there were over 25000 signalling failures causing delay. The delays incurred add up to 760000 minutes (about 12600 hours) [6]. With a financial cost associated with delays which can be as much as US \$80 per minute of delay [2], the total cost of the delays in UK amounts to almost \$61 million for the year 1999-2000. Considering the current hourly wages of urban workers, this amount is probably close to \$100 million today.

It is therefore clear that there is a need for a completely new safety system that improves safety while reducing infrastructure and maintenance costs.

In this paper, we argue that a biologically inspired solution exists for this longstanding problem. Inspired by self-organizing biological systems [7] such as fish schools, bird swarms, and social insect colonies where the members of the colony are able to move and avoid collisions among them-

selves, we propose a solution for safety of railway transport that works in a similar manner.

A biologically inspired self-organizing system has recently been proposed to coordinate traffic at road intersections [8]. Although, due to the specific constraints of railway transport, this approach cannot be directly applied to railway transport, we have found a biologically inspired solution that can improve railway safety and at the same time reduce the cost of traffic control substantially.

The next section briefly discusses the principles of self-organizing biological systems and how they can be used as inspiration for designing cooperation mechanisms for coordinating rail transport traffic. We then compare the characteristics and constraints of railroad transport and road transport. Afterwards, we present our solution for railway transport and finally we discuss how this solution overcomes the existing railway safety concerns.

II. NATURE AND TRANSPORT

Biological systems in nature are distributed and self-organized; decisions are not taken by only a particular member or the leader of the system, but by the collective or the colony [7]. As described in [7], they are dynamic, as the situation is continuously changing and the members have to adapt “on the fly” to the changing conditions. This requires continuous interaction and cooperation among the members of that biological system or colony. Although the action of each member corresponds to simple rules, the aggregate behavior of the whole system can perform very complex tasks because of the nonlinear interactions caused by these simple rules. They depend on “pre-programmed” parameters intrinsic to the organism as well as the environmental situation that has a very important impact on the end result of the actions and interactions.

There are interesting similarities between biological systems and transportation: both of them are mobile dynamic systems that need to adapt to the situation and the environment. Visually, this can be seen in videos of biological systems that can be found, for instance, on ‘youtube’. A fish school [9] and a bird swarm [10] can serve as inspirational examples. From the very simple movement of each member a globally perfectly coordinated movement emerges that looks poetically beautiful and complex. Figure 1 shows a photo of a bird swarm of starlings, where two flocks of birds flying in opposite directions can be observed.

Just like in these examples, in transportation also it is necessary to avoid collisions. Moreover, this global movement is efficient: since members are very close to each other, they can adapt to the new situation quickly and on a global scale. In this manner, collisions can be avoided even if members move in opposite directions.

Our goal in this paper is to design and engineer such efficient movement in railway transport as well so that dangerous situations and safety hazards could be avoided in an efficient and timely manner.

Fig. 1. A swarm of starlings, self-organizing to complex formations [10].

Before proposing a biologically inspired solution to the railway transport problem, we consider the main characteristics and constraints of the railway transport and compare it to road transport. Table I summarizes this comparison.

	Road	Railway
Reaction	Fast change of direction and speed	Very slow change of only speed
Intersections	Single intersection	several switches in shunting yards
Communication range	covers the intersection (≈ 250 m)	may not cover a shunting yard (≈ 5 km)

TABLE I
REQUIREMENTS OF ROAD AND RAILWAY TRANSPORT

III. PROPOSED SOLUTION

Inspired by nature, in this section we propose a new self-organizing approach to control railway traffic. This system should allow rolling stocks to behave in a similar way as bird swarms, fish schools, or social insect colonies, except for the specific constraints of train transport. Such a system can increase efficiency, i.e., trains may travel close to each other while safety is guaranteed.

A biologically inspired railway traffic control system should regulate the traffic in a fully distributed and cooperative manner where rolling stocks are collaborating continuously. The rules that define the behavior of the system must be simple, but at the same time allow handling complex situations. The rolling stocks should have a-priori knowledge of what they should do, but should also be able to adapt their behavior according to the situation.

As the trains are incapable of changing direction and typically require long braking distances, our proposed solution regulates the speed of the trains to obtain a harmonious movement of all rolling stocks. This approach is composed of a two-level algorithm, representing the “simple rules” typical in biological systems. The first level controls local behaviour and the second level controls the global behaviour. Both shall be described in the following:

First-level algorithm

The continuous interaction of the members of the biological systems is achieved by a beaconing scheme in our approach. Rolling stocks send periodic beacons to their neighbors informing them about their movement and intentions. This way, traffic can adapt to any local change. This works in a similar way to birds continuously monitoring the distance to the other birds and maintaining a safety distance to avoid fatal collisions. For monitoring the environment, fish use their visual and hydrodynamic perception of their lateral line. These “sensors” provide the necessary input for the collision avoidance. Analogously, rolling stocks will rely on all the information received via wireless communications.

Fig. 2. A potential collision scenario with unidirectional motion of trains

Figure 2 shows a scenario where collisions are avoided. In Figure 2, Train 1 is a freight train with an old locomotive model, thus its speed is moderate. It sends a periodic beacon that contains information about its own position, direction, destination, speed, size and other relevant information. Train 2 is a train with a brand new locomotive travelling with a higher speed than Train 1 in the same direction on the same rails. When it approaches Train 1 and comes into its communication range, it receives the information of Train 1 and realizes that its speed has to be reduced. Approaching Train 1 in this manner, a potential collision can be avoided. Train 2 has to stay away from Train 1 by at least the safety distance. The safety distance corresponds to the minimum distance necessary to brake. It depends on several parameters like the type of brakes, speed, weather conditions and possibly others [11]. The first level algorithm is shown in Figure 3 as a flowchart.

The first level algorithm is being currently developed at the German Aerospace Center (DLR) in a system called Railway Collision Avoidance System (RCAS). In May 2010 a demonstration of the RCAS system was conducted. A video on this demo and the details of RCAS can be found in [12].

Second-level algorithm

The second-level algorithm controls the global behaviour of the rolling stocks, which is important when there are several rails with many switches and bifurcations and multiple rolling stocks. In such a complex situation, the risk of an accident may be higher. Here, we are inspired by the bird swarm shown in Figure 1 and how they move in a harmonious way [10].

Fig. 3. Flowchart of the first level algorithm.

This algorithm is particularly relevant in a zone where the topology of the rails exhibits special characteristics: the area around a bifurcation or a group of bifurcations (shunting yard) with a length comparable to the communication range. In the remainder of this paper, we will call this the “conflict zone”.

Its basic operation is similar to a birth-death type of random process with n states, n being the number of trains within the conflict zone. When a train arrives in the conflict zone, n increases by one and when a train leaves the conflict zone, n decreases by one. As long as n remains constant, the system is in the steady state.

Each conflict zone in this case has to have a leader, responsible for the communication with the incoming new system members. For each increasing transition, the leader of the network informs the newcomer about the status of the network so that the newcomer can coordinate. Then, a new leader is selected.

The whole second-level algorithm works in the following simple manner:

- 1) When a train (a “newcomer”) enters the conflict zone, it sends a broadcast message asking for the status of the network.
- 2) The current leader, if there is any, answers with its own information.
- 3) Based on the information provided by the leader, the newcomer computes the deceleration and maximum speed it needs to move with. Accordingly, it adapts its own speed so that it crosses the potential conflict point after the leader. This step ensures that the newcomer coordinates with only the current leader as opposed to several trains that might be present in the Region of Interest (RoI).
- 4) The newcomer becomes the new leader.

The flowchart of this algorithm is shown in Figure 4.

A special case for this algorithm is the following: When $n = 0$ and the first train arrives in the conflict zone, it broadcasts a message asking for the status of the network. Since there is no other train in the conflict zone, the train will not receive any reply and it will continue its journey, it will elect itself as the

Fig. 4. Flowchart of the second level algorithm.

leader of the network. Now $n = 1$ and when a second train arrives in the network, it sends a broadcast message asking for the status. This time, the first train will answer, and Train 2 will coordinate with Train 1, so that the stability of the system is guaranteed. This works because the probability of two trains entering the conflict zone at exactly the same time is zero.

Note that underneath this algorithm, the first-level algorithm is running to solve possible local conflicts if there are small changes.

Figures 5 and 6 show how the second-level algorithm works in a concrete example with three trains. For simplifying the presentation, in this paper we assume that the interlocking functionality needed to ensure that the switch is in the right position (i.e., straight versus deviation position) can be performed by the trains in an autonomous manner using wireless communications. This allows us to focus on train-to-train communications based traffic control in rail transportation.

In Figure 5, all three trains are going through the same conflict zone. Train 1 is the first leader and does not change its own speed. After it arrives at the conflict zone, suppose that the second train arriving in the network is Train 3. Its speed is very high, but it has to slow down so that it does not collide with Train 2 at the bottom right track. When Train 2 comes

into the conflict zone, it does not need to adapt its speed to the speed of Train 3, since they are not sharing any track and there is no potential conflict (assuming Train 2 is destined to go straight).

Fig. 5. Avoiding a collision at two conflict points A and B with three trains headed in the same direction (unidirectional motion)

Figure 6 shows again the same conflict zone as in Figure 5, but here, trains are travelling in opposite directions. Suppose that Train 1 is the initial leader of the network. Train 2 coordinates with Train 1 so that the latter crosses to the top right track before Train 2 reaches the top left track. In other words, Train 2 reduces its speed to avoid a collision. Train 3 which arrives later coordinates with only Train 2 (the new leader) so that it reaches the bottom right track after Train 2 has already left it.

Fig. 6. Avoiding a collisions at two conflict points A and B in the case of bidirectional motion

IV. DISCUSSION

The proposed biologically inspired solution is fully distributed and does not need the installation of track equipment, in contrast to the state of the art signalling used in railway safety systems. This has a clear advantage in terms of cost.

Moreover, the proposed system is much less likely to fail. Failure in signalling may occur due to hardware malfunctioning, which caused, for instance, the often cited accident near Wenzhou, China, on July 23, 2011. There, two trains collided due to such malfunctioning and killed 40 people. Another important source of accidents is human error; e.g., when the driver misreads or overlooks a traffic light indicating to stop. One of these kind of accidents occurred only recently in Oakland, California, on October 12, 2011 where 18 people were injured in a frontal train crash. The solution we propose in this paper mitigates such possibilities substantially. Below, we elaborate on this:

The main causes for signalling hardware malfunctioning are failure on the electrical supply, and damage or robbery of hardware and cabling. Depending on the country, theft of hardware may not be a minor problem.

To put things into perspective, Figure 7 shows an example where hardware malfunctioning causes a crash. Train 1 is travelling into Block 2. Train 2 is already situated in this block;

the hardware in charge of detecting the presence of rolling stocks in Block 2 and transmitting this information to Block 1, however, is malfunctioning. Hence, the driver of Train 1 sees a green light and goes into Block 2. When the driver of Train 1 sees Train 2, it is already too late to brake on time and the collision cannot be avoided.

Fig. 7. Collision due to hardware malfunctioning of the railway signalling system

In contrast, the solution proposed in this paper would warn the driver of Train 1 much earlier about the presence of Train 2 and there would be enough time to brake and to avoid the accident.

In the case of human oversight (not seeing, misreading or misinterpreting signals), the biologically inspired safety system proposed can continuously adapt the speed of the rolling stocks in a smooth manner, as beacons are received periodically and at short intervals (e.g., every 100 ms). Even if one message is lost, the repetition of the message will still allow for a working system as the communication range clearly exceeds the necessary safety distance. Therefore, unlike the signals in the current rail traffic control systems, there is no need to stop or abruptly change speed.

In addition, the level of integrity improves when the biologically inspired algorithms are used. Since the system is inside the train, malfunctioning of the system is much simpler to detect than if the hardware would be next to the tracks as in the case of signalling.

Moreover, the proposed solution has a huge advantage when it comes to prevent theft of hardware. As there is no hardware on the tracks, but only built into the train (sensors and communication units), it is much more difficult to steal the hardware.

Efficiency of traffic is another advantage. The maximum speed allowed within a block is the one that allows the train to brake within the traffic light signal's visibility distance. In the absence of signals, the speed can be much higher, especially where the visibility is not clear enough. The only speed limitation will be dictated by the communication reliability and the communication range.

Furthermore, the proposed biologically inspired algorithms can save energy and time as compared to the signalling train control system.

It is important to mention here that the proposed solution can be used as an additional safety system on top of the current infrastructure-based traffic control system. This appears to be feasible even in the near future. It might be possible that

the proposed self-organizing infrastructure-less traffic control paradigm can eventually replace the infrastructure-based signalling system currently used in railway transport. Such a paradigm shift has significant implications:

- i Reducing the cost of safety significantly by migrating infrastructure-based traffic signals into trains and using vehicle-to-vehicle or train-to-train communication at 460 MHz;
- ii Increasing the energy efficiency of railway transportation by mitigating the number and rate of decelerations and accelerations trains have to go through at switches or other points of conflict;
- iii Mitigating the delay at switches or other points of conflict, thus reducing the travel time of trains between cities or within a city;
- iv Supporting a greener environment by eliminating the need for sensors on the tracks and infrastructure-based traffic control;
- v Enabling ubiquitous traffic control, thus increasing the safety of railway lines known as "dark territory" which currently have no signaling system.

V. CONCLUSION

Railway transport is a very energy efficient means of transportation. Hence, this kind of transportation should be promoted over other forms of transportation, such as road transport. However, train transport is very costly; in particular, the cost of the current safety system, known as signalling is quite high. In this paper, a biologically inspired new approach to traffic control is proposed that can increase the safety, improve the energy efficiency, reduce the delay at points of conflicts (switches), and reduce the cost of traffic control substantially in railway transport.

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