Chapter 1

Introduction

1.1 Background

The railway is believed to be the most economical among all transportation means, especially for the transportation of mineral resources. In South Africa, most mines are situated inland, so heavy haul trains are required to transport these resources to harbours. It is presumed that the cost is less with a larger quantity of load per car or per train in terms of the schedule and the number of people involved. This has resulted in the use of long trains with multi-locomotives.

Traditionally, the operation of such multi-locomotive trains with pneumatic braking systems is in essence a simple one. The brake control signal is transmitted throughout the train wagons, which results in the same effort command of all the wagons. All the locomotives also have to make the same efforts, for the remote locomotives (groups) are operated in tandem with the leading one. In this operation there are only two control signals, one for locomotives, and the other for wagons. There are two prominent drawbacks with such an operation method.

1) The locomotives are distributed, but the power is not distributed independently.
2) The wagons' braking system is pneumatic and the braking control signal is propagated to each wagon through the air pressure change along the air pipe running throughout the train, which leads to different time delays in braking the wagons.

These drawbacks result in slow running speed, the possibility of derailment and a limit on the train length.

The first disadvantage is eliminated through the employment of the (independent) distributed power (DP, iDP) traction operation, in which the traction powers of the locomotives are different.

The second one was also provisionally solved with the application of new technology in the 1990s. To improve the train performance (the second of the above disadvantages), the Association of American Railroads developed a new braking system – the Electronically Controlled Pneumatic (ECP) braking system, in which the brake command signals are electronic and are received by all the wagons simultaneously although pneumatics are still used to supply the brake power. Spoornet, one of the train operators in South Africa, is the first railway in the world to roll out the ECP braking system (on its COALink line) on a large scale. The introduction of ECP braking systems can be seen in [1, 2]. Operational advantages follow the application of ECP braking systems [1].

1) Wheel and brake shoe wear can be reduced with an appropriate distribution of braking and pressure control;

2) Energy-efficient operation can be reached with the use of graduated release capability to eliminate power braking;

3) The safety level can be increased with the accurate control of the whole train and decreased stopping distance;

4) The in-train forces can be reduced owing to the complete brake control of every car of the train.

At present, such a heavy haul train in South Africa is composed of about 200 wagons and it is about 2.5 km long. A train running on the COALink line of Spoornet is shown in Fig. 1.1. It is exactly because of the above advantages that extremely long trains (up to 10 km in length) are considered in the business plan of Spoornet of South Africa on its COALink. This increase in train length has posed unprecedented technical challenges.

According to [3], train handling includes the start phase of the train, the speed maintenance phase, and the stop phase of the train. Since the railway track is long and the train is running in the speed maintenance phase during most of the running time, the train scheduling of the speed maintenance phase is the focus of this study. In realizing optimal management of in-train forces, it is justifiable to assume that a steady state of train motion is reached and held. In this study, the term "scheduling" is borrowed from the railway industry for train operation and handling, where it refers to the decision of a driving sequence in terms on locomotives' power notches and wagons' braking pressure along a specific railway track. In the context of control systems, this "scheduling" activity is interpreted as an open loop control design, which brings the train to an expected motion trajectory.

For heavy haul trains, energy consumption, running time and in-train forces between the neighbouring cars are of much concern to transportation corporations. The

Figure 1.1: A heavy haul train of Spoornet, South Africa

energy consumption is related to the direct economic profit while the running time determines the quality of the service. In-train force control contributes to the safe running of the train and to limiting maintenance cost. The larger the in-train force is, the higher the maintenance cost. For long trains, this is even more important. It is also more difficult to control the in-train forces of a long heavy haul train. It is noticed that the in-train forces depend both on the driving speed and on the power/brake distribution along the train. This is why the independent Distributed Power (iDP) operation and ECP braking systems have been introduced into practice.

1.2 Literature review of train handling

A frame for train handling is shown in Fig. 1.2. In train handling, various studies have tried to achieve different objectives.

For energy consumption, some studies have been done in [4, 5, 6, 7, 8, 9] for a train to travel from one station to the next one in a given time. In most of these papers, the locomotives are supposed to have three discrete control settings: power, coast and

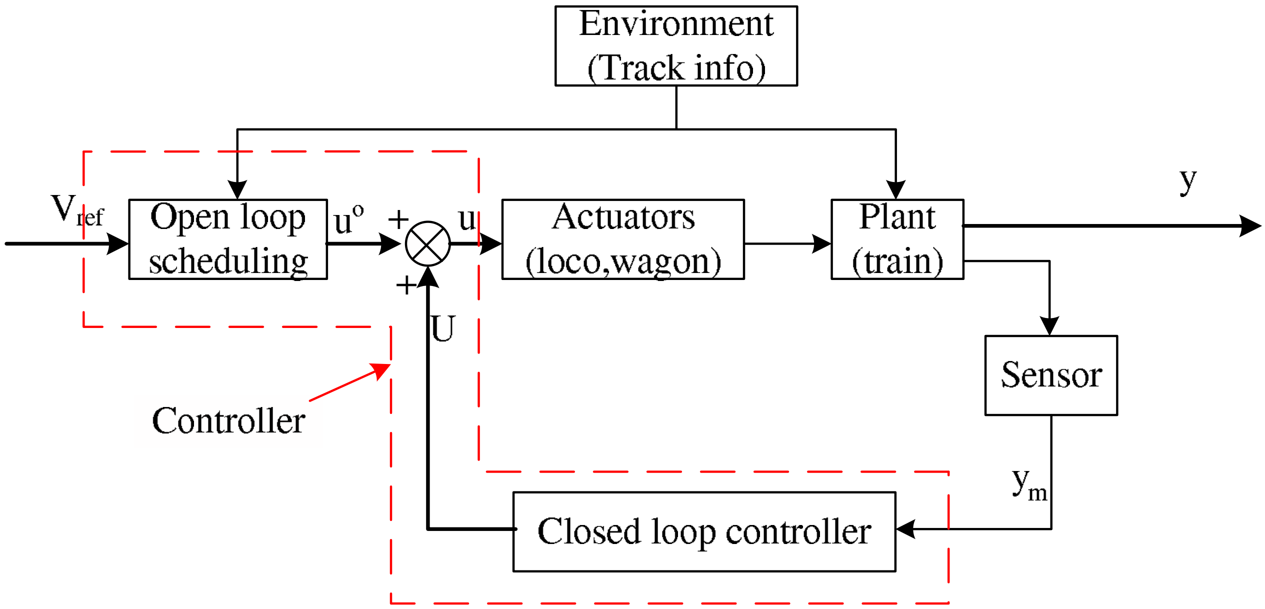

Figure 1.2: Train handling

brake. A finite sequence of the locomotive settings is arbitrarily predetermined and then the optimal algorithms are to determine the switching points where the control setting changes. Recently, an analytical approach has been proposed in [10] to find the control switching point. A train is modelled as a mass point in these papers. It is shown in [6] that a train with distributed mass can be treated as a point mass with actual gradient profile replaced by an *effective gradient acceleration*. In these papers, the dynamics within a train are ignored and speed tracking and in-train forces are not investigated.

The other models a train as a cascade of mass points connected with couplers, for example in [11, 12, 13, 14, 15]. This model is more accurate than a mass-point model for a train 2.5 km long. In these papers, a desired speed profile along a given track is assumed first. The subject of the studies is to design controllers to maintain the desired speed with some objectives considered.

For high speed (passenger) trains, speed tracking is the most important. The studies can be seen in [12, 13, 14]. In [12] [13], the H_2/H_∞ method with full state feedback is employed to deal with the cruising of high speed trains. The objective is to maintain the train speed as expected. Cruise control is proposed for two types of high speed trains, distributed driving with each car having its own driving force, and push-pull driving only with driving forces at the first and the last car. A calculation method to determine equilibrium point for distributed driving is given. Even though the push-pull driving is also taken as a way to operate heavy haul trains, again, this paper does not present optimal scheduling of equilibrium points. In [14], similar to [12], different input/output decoupling problems for high speed trains are studied. To get the equilibrium point, it is assumed that one of the in-train forces is zero or the driving force is equally distributed to the locomotives. This assumption leads to a heuristic trim point. In these papers, a train is considered as a cascade of mass points connected with nonlinear couplers. This model can be used to study the dynamics within a train. However, the in-train forces are not emphasized in these papers because they are not particularly important for such short trains. Without ECP technology, the application of these control approaches to heavy haul trains is hindered by the control signal transmission delay.

An early study of in-train forces can be seen in [11], where an LQR optimal algorithm is employed to minimize the coupler forces and/or velocity deviations from the reference values. It is assumed that at the nominal point, the nominal input vector consisting of throttling and braking forces to maintain the nominal speed, is equal to the sum of the resistance and gravity forces. Then a linearized model is used to calculate the control law. Considering the large number and the constraints of the variables, the train model is simplified. This paper offers an excellent setup to deal with the in-train forces and various calculations of optimal closed-loop control. While closed-loop control is used to optimize the interplay between in-train forces and speed holding, the scheduling of the desired holding speed is typically determined through an open loop controller design. It is noted, however, that the off-line open loop scheduling in [11] is a rather heuristic one, without making optimal use of the control redundancies. The closed-loop control is designed based on full state feedback, and with two crude assumptions for the insufficiency of the measurement of the states, the closed-loop controller is simplified to full speed feedback. Even for speed, it replaces all cars' speeds with the limited number of locomotives' speeds.

It is quite interesting to note that the early study of [11] takes into consideration some practical aspects of ECP and iDP even though the ECP/iDP technology is not implemented in practice on a visible scale. However, the model in this paper is largely simplified by taking variations due to track slope and curvature changes as model disturbances. New technologies, such as the Global Position System (GPS), make the information readily available.

In [15] and [16], based on a cascade point mass model, which is validated in [17] with the operational data from Spoornet, an LQR approach is employed to optimize the in-train forces, energy consumption and velocity tracking of a heavy haul train equipped with an ECP braking system. Considering the constraints of control input channel number, a concept of fencing is proposed. In off-line scheduling, the equilibria are calculated under the assumption that the driving force is equally distributed to the locomotives while all the braking forces of wagons are zeros and the braking force is equally distributed to the locomotives and wagons. This open loop scheduling is heuristic, too. With the discrete quantities of the locomotives' efforts considered, the efforts of the locomotives are almost always equal.

In [18], flatness-based methods in [19] are used to design the open loop control schemes for a heavy haul train, where a train is taken as an infinite dimensional linear model.

The off-line scheduling for the equilibria in the above papers is based on some heuristic assumptions without considering the optimization of the equilibrium. The difference among the different equilibria is of course not discussed.

The heuristic scheduling way may lead to irrational power distribution, especially when one locomotive group is climbing uphill and the other one is driving downhill. Assuming a train composed of some wagons with one locomotive at the front and one at the rear is running over a hill (the front part is driving downhill while the rear part is climbing uphill), it is expected that the front locomotive is braking and the rear one is powering and thus the in-train forces are small. However, with the above heuristic scheduling, the efforts of the front locomotive and the rear one are always the same, which may lead to irrational power distribution. An extreme example is shown in Fig. 1.3.

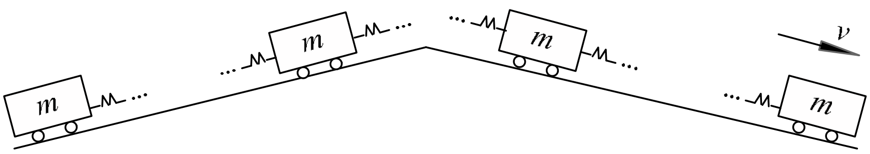

Figure 1.3: Irrational power distribution

With open loop scheduling, the running error always exists and it sometimes leads to oscillation, which should be avoided in train handling.

The methods to design closed-loop controllers in the above-mentioned papers are all within linear system theories and based on linearized models. The closed-loop controllers are in the form of state feedback or in the form of measurement feedback with some crude assumptions. In train handling, only some speeds of the cars are practically measurable. A closed-loop controller based on speed measurement feedback is necessary.

In the above papers on train handling, all the controllers are designed on the assumption that the train is well set up and all the actuators (traction efforts and braking efforts of locomotives and wagons) and sensors (speed sensors) work as designed, which is an ideal condition. In practice, some of the actuators and/or sensors may be faulty, and even worse, the train structure may be changed. For example, the speed sensor has a constant bias, or the amplifier in the sensor circuit has a fault, which leads to a gain fault in the sensor. The locomotive may fail during the running, which happened in the ECP trial run to collect data to validate the cascade-mass-point model in [17] on 18 November 2003. In the stop distance calculation of the collision mentioned in chapter 2, one locomotive was not functional during the running. The air pressure in the braking pipe may be different from the expected one because of the pressure sensor fault in the pressure recharge system or the air leakage, which makes the braking forces acting on the wheels less than expected.

When this happens, the controller, designed on the basis of the faultless train model, cannot work as well as expected, and sometimes it even leads to unsafe running, such as train-breaking and derailment. The safe running of trains cannot be promised, so some safe running methods need to be applied in train handling.

1.3 Motivation

From the above, it is evident that there are some problems in train handling.

1) Optimal scheduling in the calculation of the equilibria of the nominal model. According to the literature, there are several scheduling methods. However, there is no comparison among them and it is not known which one is the best or if there is another better one. This step is very important because it is hoped that good open loop scheduling will present a good starting point and it can improve the performance of the closed-loop controller.

2) The design of a closed-loop controller with speed measurement feedback.

3) The fault-tolerant control problem of the designed controller.

It is assumed that there are redundancies in designing an open loop controller. An optimization procedure is applied in this thesis to schedule cruise control by taking the in-train forces into initial design consideration. It is hoped that an optimal open loop controller design will present a better starting point for a closed-loop controller design. A type of LQR controller with state feedback is simulated to justify the above redundancies.

However, the closed-loop control law is designed based on full state feedback, which is not practical since not all the states can be measured.

An observer could be designed to supplement the LQR controller if partial states are measured. This is, however, not the approach taken in this study. Instead, the application of output regulation of nonlinear systems with measured output feedback to the control of heavy haul trains is considered. The optimal scheduling of the open loop controller is still based on "trading off" the equilibria. Thus the precise balance between energy consumption and in-train forces is still maintained by the choice of weight factors in the optimal scheduling. For closed-loop control, the speed regulation is imposed. This approach to design is practically feasible and manageable, and by its nature, is also easily integrable with human drivers, if it works as expected. Instead of the linear system theory, a nonlinear system theory is adopted, implying without a linear approximation philosophy, the control is closer to reality. Another advantage of the approach is the assumption that only the locomotives' speeds are available for measurement.

For the last problem above, model-based fault detection and isolation (FDI) is employed in this thesis for sensor faults and braking system faults. Based on the fault signals of the FDIs, the controller designed with output regulation can be redesigned to make it fault-tolerant.

The above indicates that this study is undertaken to find a driving methodology for the implementation of a given speed profile for the train. In the controller, the energy consumption, in-train forces and speed tracking are taken into account. Considering the possibility of failures of sensors and actuators, the controller should be fault-tolerant.

1.4 Contributions of thesis

In this study, the contributions are as follows,

1) One first assumes and validates that the optimal open loop scheduling can improve the performance of the closed-loop controller compared with the existing heuristic scheduling.
2) The output regulation problem of nonlinear systems with measured output feedback is formulated and solved for the global version and local version. This has extended the existing theory of the output regulation problem and it is applied to train control.
3) The result of output regulation of nonlinear systems with measured output feedback is applied to train handling. Some necessary designs for the application are undertaken.
4) Taking into consideration the possibilities of the failures of the sensors and actuators, fault detection and isolations for the gain faults of the sensors and the braking systems are designed. Based on the fault signals from FDIs, the speed regulator can be redesigned. Thus, the controller is fault-tolerant.

1.5 Layout of thesis

This thesis includes six chapters. In this chapter, the background of train handling is described first and followed by a literature review on train handling. Based on the literature review, the problems in train handling are identified and some approaches are proposed for them. The contributions of this thesis are presented last.

A train model is described in chapter 2, where the longitudinal dynamics of a heavy haul train is modelled as a cascade of mass points connected with couplers. The mathematical model is given, as well as the state constraints and input constraints. The second part is about the calculation of the emergency stop distance in a collision. A mass-point model and a cascade-mass-point model are used respectively. From a comparison of the calculation result, it can be seen that the cascade-mass-point model is more accurate for a train longer than 1.8 km.

In chapter 3, three control strategies are proposed first. Then optimal scheduling taking the in-train force into consideration is developed and simulated for trains equipped with a traditional pneumatic braking system and an ECP braking system, respectively. This is followed by a comparison of optimal scheduling and heuristic scheduling. The simulation result shows that optimal scheduling presents a better starting point for closed-loop control, which is confirmed with an LQR controller.

A speed regulator (closed-loop control) with measurement feedback is proposed in chapter 4 for train handling. The output regulation problem of nonlinear systems with measurement feedback is formulated and solved in the global version and the local version in the first part of this chapter. In the second part, some application issues of the result of the local version to train handling are discussed.

The fault-tolerant control of heavy haul trains is investigated in chapter 5. Firstly, the fault detectability algorithm is quoted from [61]. Based on this, the fault detection and isolation of the sensor gain faults are designed. The fault detection and isolation for the braking system faults are designed based on an analysis of the steady-state speeds. The fault signals for locomotives are assumed to be given. With these fault signals, the speed regulator is redesigned. Finally, the simulation for different kinds of faults proceeded.

Chapter 6 is the summary of this thesis and presents some discussion of further studies in train handling.