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IDISRA – Integrated Distributed Intelligent System for Rail Automation: Safety Issues

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***Abstract*—A *novel Integrated multi-layered network and cooperative computation based Distributed Intelligent System for Rail Automation*, IDISRA, is proposed for safe, reliable, efficient and automatic train operations. The objectives are, i) distributing the load from a central server located at a signal house to a neighbourhood of nodes to avoid bottleneck, ii) making the signals intelligent having to-and-fro communication, storing and analyzing capability, iii) integrating the communication mediums from rail to optical fiber to wireless sensors to enable multi-layering of the network, and iv) integrating the multi-layered network based on p2p communication and nested addressing system to enable cooperative computation for local and instant decision making. The multi-layered network combines networks like signal network, station network and junction network. This system can monitor and control local incidents through intelligent signals and sensors to detect early and recover from any emergency situations like node failure, track hazards, fog, fire, collision, sabotage and terrorist activities by providing alternative backup solutions. IDISRA is basically a founding block based on which an overall train operations management system including automatic train movement can be developed. The system eliminates most existing external trackside equipments. The current work focuses on the safety related issues of IDISRA.**

***Index Terms*—Cooperative computation, fault tolerance, multi-layered network, p2p, sensor, signalling**

I. INTRODUCTION

There are wide ranging causes of train accidents which include human failure, track damages, failure of the engine, coach coupling, signal or interlocking unit, communication network failures, information security breaches, natural calamities, sabotage and terrorist actions. The systemic reason behind accidents is the poor state of operation, maintenance, management, quality of equipment and communication network or faulty design of the system. The central issue involved in designing a system for smooth operation of automatic train movement is the communication network and the efficiency of the computation supported by proper security backup. The communication system needs to involve railway hardware and equipment of a great variety and a highly complex and vast network covering several hundreds of railway stations with tracks running thousands of kilometers sometimes across nations or continents, thousands of signals, operating staff in thousands, hundreds of trains running at variety of speeds and carrying millions of passengers on daily basis. The computation is required for automatic control of the speed and direction of the train on a real time basis to maintain the schedule and smooth passage of the train, e.g. reducing the train speed due to bad condition of track or weather, selecting the track or making last minute changes to the route due to temporary closure of some sections of the rail network. A smooth, safe, automatic, reliable and efficient operation of train movement along with adequate provision of manual intervention helps in maximizing overall train speed and minimizing casualties.

A NEtwork-based Signal Control System for Automatic Block Signals is discussed in [1] on the basis of a signalling system that controls the field devices through an IP network [2]. These technologies use centralized control system to operate the interlocking and their corresponding signals. An application of assurance technologies that is necessary to coexist with the existent interlocking device over the period of construction and operation is described in [3]. It consists of a central control unit called LC (logic controller) and terminal devices called FC (field controller) that are distributed at the trackside and operate signal devices. The Internet and optical LAN technologies are used for communication between a LC and corresponding FCs. Here the term ‘distributed’ is used to imply the scattered position of the FCs. A recent work [4] describes a railway signalling system utilizing ip-based communication network and autonomous technology being implemented in a Japan railway. The FC decodes the control data from the LC and electrically controls the signal device's behaviour. The FC then returns the result data back to LC. The FC also monitors status of the signal device and sends a monitoring data to a remote server.

From the above it is seen that currently the railway signalling systems are basically centralized systems

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which have some inherent weaknesses affecting overall performance associated with centralized control and operation. These are heavy load and bottleneck at the servers, frequent system crashes, and lack of flexibility in designing systems. A distributed system on the other hand has been found to be more efficient and reliable, scalable, flexible (e.g. it can add or adapt to newer networks or systems), allows point to point connectivity, empowers locality of operation and more equitable sharing of resources and thus enables cooperative and intelligent computation. Each of these features is suitable for a big and mixed network like that of a railway system. We thus propose a distributed system as follows.

A novel Integrated multi-layered network and cooperative computation based Distributed Intelligent System for Rail Automation (IDISRA) where the computations and communications are mostly local (Locality here is defined according to the level of the network that the node belongs to.) is proposed. The computation would be carried out by *autonomous* yet *cooperating agents* representing entities such as moving trains, signals, track interlocking units, stations and even human agents like drivers and station masters. Neighboring agents directly communicate with each other like peers for a cooperative cooperation required, e.g. for determining the speed of the train or directing the interlocking unit for allocation of a track to the approaching train. The neighbourhood structure is dynamic because of continuously shifting locations of moving trains. We propose to use our own addressing mechanism unlike many recent systems which use ip-based networks [1]-[4]. The problems mainly security with using ip-address for railways were mentioned as early as in 2003 [5].

A. Contribution

IDISRA uses a multi-layered network which integrates constituent networks as sensor network (at the lowest level), signal network (at the next level), station network, junction network, and so on. This is a p2p based distributed network. It uses a nested addressing system. Each node has a well defined neighbourhood which either spans the network at the same layer as the node belongs to or spans across other layers depending on the need. The neighbourhood is dynamic. The communication is possible between any two nodes within a neighbourhood. Trains, which are dynamic nodes, can also communicate with any other node, which are static, and vice versa. The communication medium differs based on the layers of the nodes. The computation is cooperative. All the nodes are intelligent. All these enable tracking the local incidents promptly if not instantly. This helps enormously improving the safety system for automated rail operation. This distributed system also enables eliminating a lot of existing track side equipment which are vulnerable to weather hazards or human interventions. The distributed network makes the system design highly flexible. IDISRA also gives a foundational framework for overhauling existing systems for overall management for the entire rail operations. We briefly present IDISRA; a full description particularly of the network and addressing mechanism is not within the current scope.

The structure of the paper is: Section II and III outline IDISRA and its communication infrastructure. Section IV discusses how the safety issues are addressed in the existing systems, while V focuses on how the safety issues are resolved by IDISRA and also explains its fault tolerance mechanism and handling of emergency situations. Section VI concludes with scopes of research.

II. IDISRA

The objective of IDISRA is to make the signalling system intelligent being reactive and responsive in real time to the immediate situation arising from incidents occurring locally. This is achieved through a p2p based communication mechanism. Train movement monitoring and control and operation of interlocking units are accomplished by means of cooperation between the stations and signals.

In this paper we focus mainly on the *safety issues*. Our *communication network* has *four levels (layers) and five types of nodes*: junction, station, signal, trackside sensor and train, all except the train have fixed location. At the highest level is the *junction network* with junctions as nodes, next *station network* with stations as nodes, then *signal network* and lastly *sensor network*. Wireless sensor devices are useful to monitor any incidents occurring locally. WSN (wireless sensor network) is introduced to reduce the occurrence of accidents and improve the efficiency of maintenance activities [6]. Existing wireless techniques used for both communications and signalling in the railway industry and low-cost, low-power WSN architecture to monitor the health of railway wagons attached to a moving locomotive is described in [7].

In our system all communications occur between peers according to a defined neighbourhood structure. Neighbourhood of any node is in general a function of node type, incoming train location, train route, train type (high/low speed), train requirement, and decisions taken by the approaching station. When a high speed train moves the neighbourhood defined till the next station may not suffice as more planning may be required compared to low speed trains. For inter-level communications the neighbourhood of a node will also contain nodes from adjacent levels, e.g. a signal may need to communicate with a station node which is at a higher level or a sensor at a lower level. Trains communicate with signals.

Stations are responsible for managing the arrival and departure of trains through the cooperative action between the station, station-entry signal and a station signal. All crossing signals belonging to a group (related to a crossing) interacts with each other and determines priority for the trains approaching the interlock and sets its interlocking mode accordingly. Similarly, all adjacent level-crossing signals in a group communicate with each other along with road signals to pass a train. Besides managing this grouping mechanism each signal passes on the message containing necessary information such as train address, train speed, etc. to its neighboring signals for smooth train movement. All these need cooperative decision making among the nodes.

Wireless sensor devices are deployed alongside railway tracks. Each of these scattered sensor nodes is capable of collecting necessary data and forwarding the same to its nearest neighboring signal. The *transmission medium* between a train and a signal or two trains running on same track is a rail. The medium between two stations, two signals, or between a station and any of its station signals is *optical fiber*. Trackside sensors communicate wireless with other sensors and signals. The external interface of this multi-layered network occurs through internet and the main participants are junctions and occasionally stations. The purpose would be primarily public communication. Appropriate *man-machine integration* would be required to take care of both regular operation as well as exigencies, e.g. maintaining up to date timetable and route databases on regional servers or reporting incidents publicly. Further for security backup each node must handle operational as well as planning data. This will help handling both exigencies and information security breaches.

Indian Railways (IR) is a state-owned enterprise, owned and operated by the Government of India through the Ministry of Railways. It is one of the world's largest railway networks comprising 115,000 km of track over a route of 65,000 km and 7,500 stations [8]. IR is divided into sixteen zones and sixty eight divisions. People employed in IR are about 1.6 million and it runs about 14,300 trains daily [9]. IR carries more than 20 million passengers and 2.8 million tons of freight daily. In 2011-12 IR earned US$ 19 billion of which US$ 12.7b from freight and US$ 5.2b from passengers. IR accommodates a variety of operating conditions, e.g. trains of varying length, engine power, source of power (diesel or electricity), load (passenger and goods trains using same tracks), running speed, stopping frequency (suburban trains as well as express trains) and geography (plains, mountains, desert and highly populated areas).

IDISRA is designed to work for a large, complex and mixed railway system like Indian Railways as well as for modern railway systems such as Japan Rail or Euro Rail. Necessary adjustments would be necessary.

III. THE COMMUNICATION INFRASTRUCTURE

We discuss here briefly the communication infrastructure of IDISRA. Our communication approach contrasts with existing three major approaches: a) the older one is *beacon based communication*. Beacons are attached to tracks ahead of the signals – location beacon for knowing train location and signal beacon for speed control. Beacon transmission is vulnerable to bad weather, electronic interference, damage, vandalism and theft; b) the more recent one uses *region based communication*. Here the train entering a region communicates with the region centre through radio transmission which suffers from interference or underground communication and also restricts size of a region; and c) some recent approaches suggest *ip-address based centralized communication* [1], [2] and [4], where the signals can receive instruction from the LCs (Here stations represent the main communicating and computing nodes and signals are mostly dumb.) and give feedback about its status – these however would not be able to find out a local incident instantly.

Different elements need to be installed at the nodes such as processor, memory, software, database and sensor. The database is required to store information such as address, distance, direction, and route for the fixed neighboring nodes, the routes to neighboring major and minor junctions, neighboring stations, train schedules, interlocking modes, etc. The sensor attached to a signal node is used to capture the speed of the passing train, a dynamic node. The software, processor and memory are required to receive data from incoming neighboring nodes, process those data, take necessary actions according to the processed data through cooperation with other nodes and send the processed data to the outgoing neighboring nodes for further processing. An approaching train indicates incoming and outgoing neighbors.

A dynamic node (train) with shifting location also requires installing a few elements. The database of the train stores its number, name, type, route, schedule, speed limit, current position, current speed, brake etc. The current position of the train can be determined from data received from fixed nodes. The engine sensor should be capable of taking necessary instruction from other nodes during its passage using the medium of rail. Also at the end of a train there should be an end-of-train marker (red) connected with the engine sensor and the connection is used to find faults between coaches.

The transmission mediums, rail and optical fiber, are required for communication between the nodes. There are several advantages using optical fiber: no radiated magnetic fields around optical fibers and electromagnetic fields are confined within the fiber. That makes it impossible to tap the signal being transmitted through a fiber without cutting into the fiber. Thus the fiber is currently considered the most secure medium available for carrying sensitive data.

IV. SAFETY ISSUES OF EXISTING SYSTEMS

The evolution of rail signalling system from track-circuit signalling to advanced Communication-Based Train Control systems, highlighting the differences, benefits and challenges with regard to improving performance while ensuring safety is discussed in [10]. The safety related issues provided by the modern equipments, interface, environmental requirements and practical considerations [11], [12] are summarized below:

a) *Track Circuit*: Low voltage currents applied to the rails cause the signal via a series of relays (earlier) or electronics (more recently) to show a "proceed" aspect. The current flow will be interrupted by the presence of the wheels of a train. Such interruption will cause the signal protecting that section to show a "stop" command. Any other cause of current interruption will also cause a "stop" signal to show. The system is sometimes referred to as "fail safe" or "vital". A "proceed" signal will be displayed only if current flows.

b) *Trainstop (Enforcement)*: The trainstop consists of a steel arm mounted alongside the track and which is linked to the signal. If the signal is red the trainstop is raised and if the train attempts to pass it the arm strikes a "tripcock" on the train applying the brakes and preventing motoring, otherwise the train can pass freely.

c) *ATP (Automatic Train Protection)*: Electronic ATP involves track to train transmission of signal aspects and their associated speed limits. On-board equipment will check the actual speed of the train and will cause slow or stop the train if any section is entered at more than the permissible speed.

d) *AWS (Automatic Warning System)*: An alarm sounds in the driver's cab whenever a train approaches a caution or stop signal. If the driver fails to acknowledge the alarm the train brakes are applied. The AWS ramp (a pair of magnets) is placed between the rails so that a detector on the train will pass over it and receive a signal.

e) *TPWS (Train Protection Warning System)*: For each signal two pairs of electronic loops are placed between the rails. Each pair consists of an arming loop and a trigger loop to detect the elapsed time that provides a speed test. In this case both loops are together so that if a train passes over them the time elapsed will be so short that the brake application will be initiated at any speed.

f) *ATO (Automatic Train Operation)*: The basic requirement of ATO is to tell the train approaching a station where to stop so that the complete train is in the platform. ATO also allows "docking" for door operation and restarting from a station.

g) *AC (Autonomous Type Communication)*: It is used in an ip-network based signal controlling system for transmission of control or feedback data between LC and FC [4]. Safety related equipments exchange the data periodically and determine their behaviour based on data received autonomously. Errors are detected autonomously and necessary actions are taken if required.

To implement the above mentioned safety measures a lot of external elements are used. Track circuit uses relays and other electronic equipment, trainstop uses steel arm or tripcock, AWS ramp and permanent or electro-magnet elements, TPWS electronic loops and AC safety related equipments. These external elements are vulnerable to bad weather, electronic interference, damage, vandalism and theft. But IDISRA uses message based communication along with cooperative computation within a neighbourhood of nodes that highly depend on the assured operation of the communication medium (rails, optical fiber) and an integrative network. IDISRA relying only on signalling components minimizes the external trackside equipments. We however are suggesting trackside sensors for enhanced safety.

V. SAFETY ISSUES OF IDISRA

Safety depends heavily on the smooth, correct and failsafe operations and behaviour of the signalling system, on board system on the train, communication network, driver and operators like station master and cabin man. In IDISRA each and every movement of a train is monitored and controlled by a number of signals and stations through communication between the nodes on its way.

Station to station communication is useful for selecting the track on which a train will run to proceed to the following station. It should be established before the train reaches the station. After selecting the track the station informs it the corresponding station signal and group of station-entry signals. The station signal forwards to the neighboring signals up to the next station signal the message containing train address, the next station address and the track number to the next station. A station can communicate with appropriate neighbours for other purposes as well, e.g. a station can communicate downwards with signals and upwards with other stations and junctions for disaster recovery.

In IDISRA a signal communicates with a train and vice versa through the rail. A signal estimates the ‘actual speed’ of the passing train from the elapsed time and the length of the train and sends it to the outgoing (next) signal through a message, which in turn computes and sends the ‘expected speed’ message to the train through the rail and the sensor of the engine of the approaching train receives the message and takes necessary action accordingly. The message also contains current position, required speed, approaching station, distance of the approaching station, distance to stop, etc. If the speed of the train is more than the permissible speed computed based on the surrounding environment and track conditions a warning is given to the driver or the automatic break is applied. This provides the same functionalities as ATP, AWS and TPWS where no steel arm or tripcock is required as in the case of trainstop or no ramp, permanent or electro-magnet elements, electronic loops are required. A train passes necessary information to the approaching signal in the same way.

A signal sends a ‘clear’ message to its previous signals when a train passes that signal. On receipt of this clear message the color aspect of these signals are changed differently depending on the minimum safe distance required between two trains which in turn may depend on the train types. Two adjacent signals continuously check availability (other than message passing) to each other to ensure whether any damages have occurred or not on the rails. This safety operation is provided in the traditional system by track circuit that consists of external trackside equipments like relays and electronic components.

Each station signal sends the ‘distance to stop’ message to the approaching train via the preceding station-entry signal. After receiving the message the ‘dynamic braking curve’ is produced and the automatic brake of the train is applied as in the case of ATO.

As already seen the centrally controlled railway signalling system in [4] is quite advanced. However, it suffers from heavy loads on the central servers (LCs) causing bottleneck. The signals (FCs) are not designed to be intelligent enough for storing and analyzing data, monitoring and controlling local incidents and taking decisions through cooperation with other signals, which these are unable to perform also because these cannot directly communicate with each other. Since it uses internet for communication it is also vulnerable to security attacks. IDISRA also provides these functionalities autonomously without having the bottleneck of a centralized system as in [4].

A. *Fault Tolerance*

These issues of IDISRA consists of '*early detect and recover*' any unwarranted situation like track hazards, node failure by providing alternative backup solution. As illustrations an algorithm for detection of broken rail and another for detection and recovery of node failure are given below.

a) *Broken Rail Detector algorithm*: IDISRA uses the difference between the speeds of two communication mediums optical fiber and rail for this.

Step 1: Every δ seconds S_1 sends a 'detect' signal to adjacent S_2 via both rail and optical fiber.

Step 2: S_2 computes 'actual delay' d and 'expected delay' d_1 between the two 'detect' signals received from S_1.

Step 3: If $d - d_1 \leq €$, S_2 sends 'ok' ack. to S_1.

Step 4: S_1 informs neighboring signals and stations that a particular block of the rail track is tampered. (δ, € are predefined thresholds.).

b) *Node failure detection algorithm*: In IDISRA the signals continuously verify the presence of neighboring signals through the optical fiber.

Step 1: Every δ_1 seconds S_1 sends a 'detect' signal to adjacent S_2 via the optical fiber.

Step 2**:** If ack. received within $€_1$ seconds do nothing.

Step 3: S_1 sends 'S_2 failed' message to neighboring stations and signals for their necessary actions (δ_1, $€_1$ are predefined thresholds.).

B. *Emergency Condition Handling*

Here we discuss how we can use *wireless sensor network* (WSN) to improve safety and security further in IDISRA, which will incorporate a WSN in its lowest layer of its integrated network. There are many issues to design a WSN for the rail system to take advantage of the local geography and other environmental conditions as well as the degree of additional safety considered necessary vis-à-vis investments and running costs required. WSN consists of spatially distributed autonomous sensors scattered besides the track to sense several exigency or extraordinary situations such as foggy or snowy weather, fire, bomb blast etc. and to cooperatively pass their data to the neighboring signals through the WSN. Each sensor should store a permissible range of operation of temperature, pressure, humidity, vibration and sound to react.

VI. CONCLUSION

IDISRA is basically a rail automation system framework which is highly flexible to work for a mixed railway system as Indian Railways as well as a modern system like Euro Rail or Japan Rail. Its distributed and cooperative computation based on an integrated multi-layered network incorporates automatically a design flexibility. The system described above (without trackside sensors) would itself give adequate safety for most systems, say for Indian Railways. But selective deployment of sensor level network will certainly help. IDISRA even though eliminates most of the existing trackside equipments it is expected to provide better safety than many existing systems. Trackside sensors easily integrate into IDISRA and hence add to the overall safety significantly, even though the investment would not be very huge. Two things need to be looked into immediately to strengthen IDISRA further: security risk and introduction of devices like RFID. In addition one can look into areas as dynamic rescheduling, optimization of time table, introduction of new routes, and expansion of the rail network.

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