Integrated Monitoring and Control System for Production, Supply Chain and Logistics Operations

Sobhi Mejjaouli[1] and Radu F. Babiceanu[2*]

[1]Department of Systems Engineering
University or Arkansas at Little Rock
Little Rock, AR 72204-1099, USA

[2]Department of Electrical, Computer, Software, and Systems Engineering
Embry-Riddle Aeronautical University
Daytona Beach, FL, 32114-3900, USA

ABSTRACT

Meeting customers' demand with the minimum cost, the required quality, and within the expected timeframe is the ultimatum goal of producers and logistics companies alike. To achieve this goal, real-time supply chain systems decisions are needed to address the inherent production, operations, and market uncertainties. Machine failures impact the producers' ability to meet their scheduled demand. Logistics delays are a significant source of uncertainty, especially when perishable items are transported with direct consequences on delivery time and quality. Real-time condition monitoring for in-transit perishable items requires an adequate infrastructure system available. Two relatively new technologies for the production and logistics domain, RFID and wireless sensor networks, provide the needed sensing, processing, and data storing and communication capabilities. When integrated, the resulting monitoring and control system may allow producers and logistics companies to considerably improve their operations by gaining more visibility for the product movement across their supply chains. This work proposes a framework for the design and implementation of a monitoring and control system for production and transportation operations. The proposed system employs the RFID-wireless sensor networks integration and is intended to provide more flexibility for production, logistics and supply chain activities in the face of uncertainties inherent during operations.

1. INTRODUCTION

Radio Frequency Identification (RFID) technology was developed decades ago, but only relatively recently entered the manufacturing, logistics, supply chain, and retailing domains. It is used for tracking and identification purposes, with the data being stored by the RFID tags and retrieved using an RFID reader. The tags are usually composed of two parts, a small chip and an antenna. The chip is responsible for data storing and processing, while the antenna is responsible for receiving and transmitting data to be read by the RFID reader [1]. Wireless Sensor Networks (WSN) are used for monitoring purposes where deployed sensors are capable of sensing and transmitting data using predefined protocols. Reference [2] defines a sensor network as "an infrastructure comprised of sensing, computing, and communication elements that gives an administrator the ability to instrument, observe, and react to events and phenomena in a specified environment." The number of applications for WSNs followed an exponential trend since their first deployment, with manufacturing, logistics, supply chain among the latest applications to benefit from their sensing and data transmission capabilities.

Based on their intrinsic capabilities, if integrated in a unitary system, the RFID and WSN technologies would be able to ensure both item identification and monitoring, so their integration presents attractive opportunities for several application domains, including manufacturing, supply chain and logistics systems. The following useful RFID-sensor network integration taxonomy was initially presented in [3]:

- Sensors integrated with RFID tags: this model adds sensing capabilities to RFID tags that use the same protocols and mechanisms for identification and data collection.
- Sensors integrated with RFID tags and wireless devices: this model ensures communication with other wireless devices and not just the RFID readers.

* Corresponding author: Tel.: (386) 226-7535; Fax: (386) 226-6678; E-mail: babicear@erau.edu

- Sensors integrated with RFID readers and wireless devices: this model provides the RFID readers the ability to sense and communicate with other wireless devices.
- Mix of sensors and RFID tags operating independently: this model assures the integration at the software layer, where data are transmitted to the same control center.

Reference [4] presents examples of RFID-based solutions in several areas, including manufacturing, pharmaceuticals, healthcare, and retail logistics where transportation of perishable items may be required. In one example, a Taiwanese fruit producer is reported to employ an RFID-based solution for monitoring purposes, which uses passive tags embedded in plastic crates that can be read during processing and active sensor tags for temperature monitoring at cooling units. Some businesses are trying today to employ RFID based solutions to improve their internal operations. Another example reports the use of real-time location systems and RFID tags to track patients, staff members, equipment, medications and refrigeration unit temperature within the healthcare facilities.

Advances in RFID technology offered logistics services providers the opportunity to offer customers the ability to track their goods while in-transit. One of the largest worldwide logistics companies offers an air freight service that tracks drugs and life-sciences goods with RFID temperature tags embedded within containers. The service enables customers, especially those who are shipping pharmaceuticals and biomedical items, to maintain shipping temperature records and receive real-time alerts if transit conditions change. Reference [5] reports that the strategic value of RFID implementation in supply chains operations relies on its capability to collect real-time data and support the decision making process. The work further reports that RFID can enhance logistics operations, business-to-business operations, business-to-consumer marketing, after-sales service, and reverse logistics. A multi-agent simulation model to investigate the benefit of implementing RFID tags on the bullwhip effect is depicted in [6]. Using a three echelon supply chain model, for a single perishable product, the bullwhip effect reported decreases significantly when real-time information of in-transit products is provided. Finally, the research reported in [7] presents the architecture of an advanced holonic manufacturing system that uses WSNs for real-time monitoring of manufacturing resources. The simulation results show that the transition to the proposed architecture may provide significant improvement in terms of productivity, responsiveness, flexibility and quality.

2. Proposed Monitoring and Control System

2.1. Proposed System Architecture

The proposed architecture considers a supply chain comprised of one producer and multiple customers located at different geographical locations. The Monitoring and Control System (MCS) is designed to:

- Monitor the enterprise operations from product manufacturing to distribution.
- Propose operational decisions based on a set of predefined objectives, such as reduced machine down times, reduced inventories, improved quality, minimized customer penalties, and avoidance of out of stock situations.

The proposed system includes a Global Control Unit (GCU), which receives data from two lower level units (Figure 1): the Production Monitoring and Control Unit (PMCU) and the Transportation Monitoring and Control Unit (TMCU). The lower level units (PMCU and TMCU) are responsible for monitoring all operations within the manufacturing plant and the transportation network respectively, and for making local decisions that do not influence the global objectives set by the GCU. Any decisions that may conflict with the global objectives are checked with the global unit for validation purposes. Using a set of algorithms, the GCU may either validate the decision or reject it along with a new proposed solution that satisfies the global objectives and constraints. Thus, the lower level units have the authority to make local decisions and cooperate through the GCU in order to achieve the global goals set of the system. These characteristics satisfy the generic multi-agent systems architecture distinctiveness, where individual agents are characterized by (1) autonomy, defined as the capability to make decisions and execute them, and (2) cooperation, which defines relationships between autonomous agents to make decisions based on mutual objectives [7].

2.2. Production Monitoring and Control Unit

The PMCU is responsible for the monitoring and control of all processing aspects within the production facility. It consists of the Production Control Unit (PCU) and the Production Monitoring Unit (PMU).

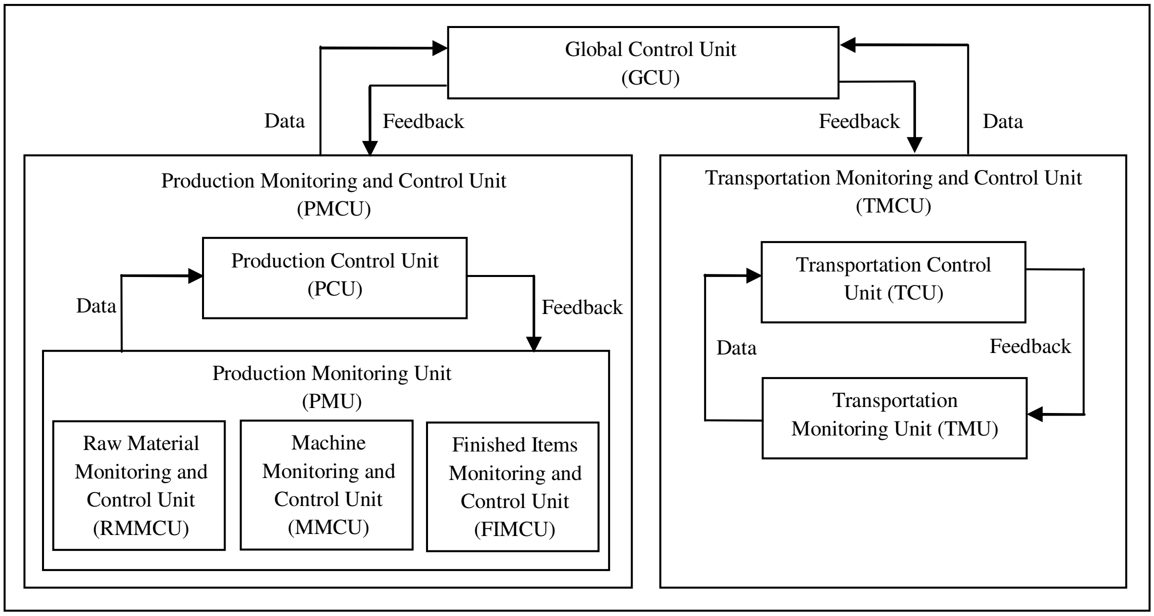

Figure 1. Internal architecture of the Proposed Monitoring and Control System (MCS).

2.2.1. PRODUCTION CONTROL UNIT

At the top of the internal hierarchy, the PCU has a global view of the operations within the production facility, tracking information such as: raw material and finished items status (inventory level, storing conditions), customer demands and deadlines, scheduled jobs, maintenance operations, and resources status such as machines availability and reliability. Based on data received from the PMU, the PCU provides decisions using a set of algorithms to achieve predefined objectives. For example, if the objective function is to minimize the items production cost, job scheduling and resource allocation decisions can be made as follows:

MIN *Production Cost* = *Labor Cost* + *Resource Cost* + *Inventory Cost*

SUBJECT TO: *Customer Demand*, *Delivery Deadline*, *Machine Availability*, *Preventive Maintenance Operations*, *Inventory Restrictions*, and *Labor Availability*

2.2.2. PRODUCTION MONITORING UNIT

The PMU is responsible for monitoring the resources necessary for production, such as raw material and machines, and the finished items. Also, the PMU can interfere with the predefined procedures through local control units to restore required conditions when failures occur. Internal to the PMU, there are the Raw Materials Monitoring and Control Unit (RMMCU), Machine Monitoring and Control Unit (MMCU), and the Finished Items Monitoring and Control Unit (FIMCU).

2.2.3. RAW MATERIALS MONITORING AND CONTROL UNIT

The duties of the RMMCU include (1) monitoring the level of inventory (quantities available for each raw material) and the storing conditions (some products for example require a specific level of humidity or temperature to be maintained when stored), which are performed by the Raw Material Monitoring Unit (RMMU), and (2) maintaining a global view of all raw material related aspects based on data from the RMMU, which is performed by the Raw Material Control Unit (RMCU). The RMCU is able to interfere with the predefined procedures of the PCU. For example, if an error occurs and the storing conditions are not maintained and differ from the specified levels (e.g., humidity or temperature go above or below their specified ranges), then the RMCU executes the following actions after detecting the error:

- Damage confinement: check the spread of the problem based on data from the deployed RFID-WSN system and identify the failure mode, its effects and its potential causes.

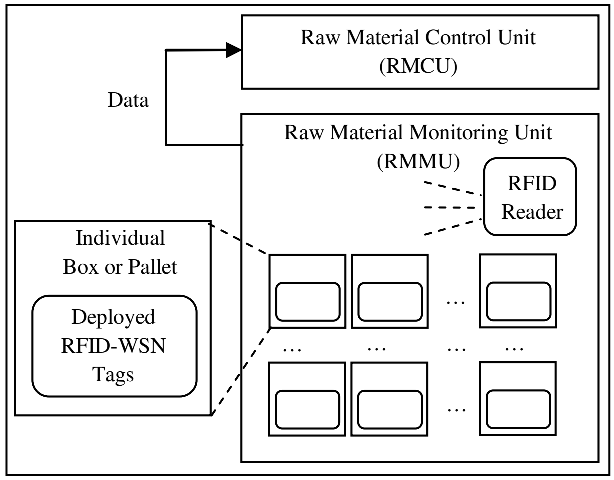

Figure 2. Internal architecture of the Raw Material Monitoring and Control Unit (RMMCU).

- Launch the recovery process based on that analysis performed on the damage confinement step, corrective actions are started to restore the desired conditions.
- Reporting and risk assessment, where a full description of the error is reported and risk assessment concerning the quality of the affected raw material is conducted to decide if the affected raw material should be kept for future use or should be disposed.

When a new job needs to be scheduled, then, data collected by the RMMU will enable the RMCU to check if the necessary raw material is available for production of the finished items and if required conditions were maintained during storage. After that, the RMCU communicates this information to the PCU, which in turn schedules the corresponding job. Figure 2 presents the architecture of the RMMCU composed of set of deployed RFID sensor tags, and RFID readers that transmit data to the local control unit.

2.2.4. Machine Monitoring and Control Unit

The MMCU duties are to perform and monitor the execution of jobs on the shop-floor, which is done with equipment that can be handling units or processing units. The processing units serve to add value to the items and the handling units will serve to:

- Feed the processing or other handling units with necessary raw materials after transporting them from the storage area.
- Transport the unfinished items within the shop-floor.
- Transport the finished items to the storage area.

The machines status and level of performance are monitored by the Machine Monitoring Unit (MMU), the global view is maintained by the Machine Control Unit (MCU), which can also interfere with respect to predefined procedures and communicate with the PCU. The RFID-WSN system is deployed within the machines areas for early detection of degradation processes (Figure 3). Deployed RFID-WSN tags provide information about the machines (identification, capacity, time of last corrective actions, mean time to failure (MTTF), mean time to repair (MTTR), preventive actions calendar) and data about the monitored metrics. For example, if high temperature is the cause of a specific failure mode, then implemented temperature RFID-WSN tags provides the MCU with the data to determine whether the machine is going through a degradation process and a failure is about to occur. If data received by the MCU show that the monitored conditions take values outside the specified ranges, above or below a certain threshold, then the MCU is able to determine that a machine went through a degradation process and the following list of actions are to be taken:

- Update the status of the resource to unavailable and stop the processing of the job assigned to it.
- Communicate updates to the PCU about the corresponding interrupted job so it can be rescheduled by assigning it to another resource or wait until the completion of corrective actions.

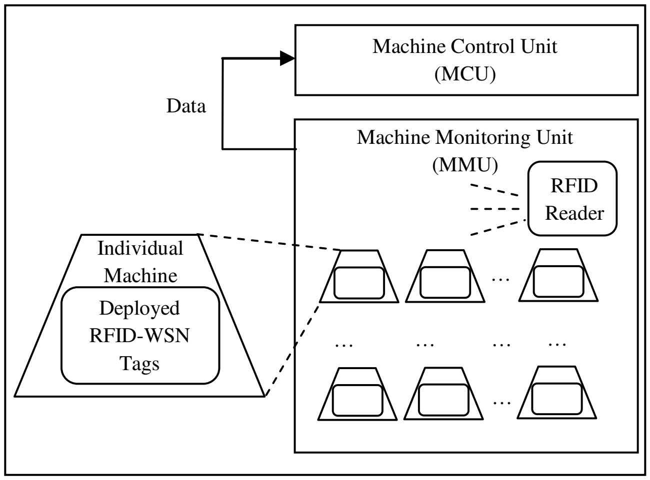

Figure 3. Internal architecture of the Machine Monitoring and Control Unit (MMCU).

- Damage confinement, by checking the spread of the problem and the portion of the resource affected.
- Launch the recovery process by investigating the resource and execute the necessary corrective actions to restore the desired condition.
- Reporting and risk assessment, by assessing the impact of the degraded resource on the unfinished items in processing at the time of interruption, and decide if they are to be rerouted in the production process, repaired and rerouted, or disposed of.

2.2.5. Finished Items Monitoring and Control Unit

Similar to the RMCU, the Finished Items Control Unit (FICU) is responsible for keeping track of the level of inventory (quantities available for each item) and for making the necessary updates when items are shipped (Figure 4). The Finished Items Monitoring Unit (FIMU) is responsible for monitoring the storing conditions and sending data to the FICU which then executes the following actions in the case of error detection:

- Damage confinement.
- Recovery process launch.

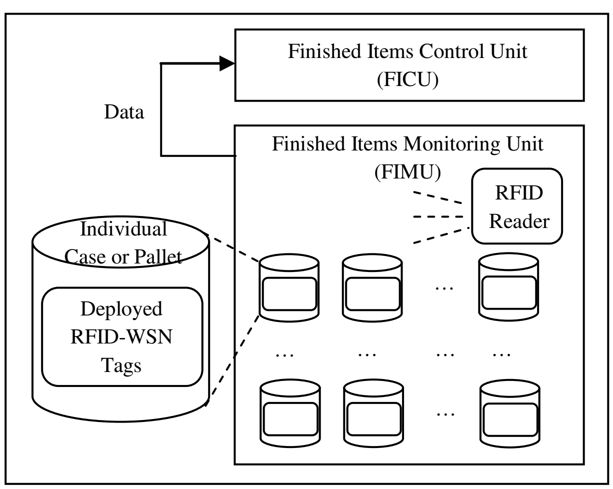

Figure 4. Internal architecture of the Finished Items Monitoring and Control Unit (FIMCU).

- Reporting and risk assessment, which in this step helps for assessing the quality of the affected items and decide if they can be shipped to customers or not.

2.3. TRANSPORTATION MONITORING AND CONTROL UNIT

During the transportation phase, the shipped items are exposed to spoilage risk. Not maintaining the required transportation conditions (i.e., vibration, humidity, and temperature) may lead to the spoilage of the shipped items. The TMCU, presented in Figure 5, is responsible for monitoring the finished items while being in-transit to the customers. Also, the TMCU can interfere with respect to the predefined procedures through the Transportation Control Unit (TCU) after receiving alerts from the Transportation Monitoring Unit (TMU).

2.3.1. TRANSPORTATION MONITORING UNIT

The TMU is designed to provide more flexibility and agility to the decision-maker when failures occur. Transported pallets or cases are equipped with RFID-WSN tags for monitoring purposes. Also, the transportation path is equipped with multiple check points in order to regularly check the items' status. These checking points are equipped with RFID readers and extract data from the RFID-WSN tags.

2.3.2. TRANSPORTATION CONTROL UNIT

The TCU has a global view of the transportation phase and all the aspects related to it, such as customer demand and deadlines, shipped item quantities, transportation start time for every shipment, the expected delivery time for each shipment, and status of items at the last check point. Based on the data received from the TMU, the TCU makes decisions using a set of algorithms to achieve the predefined objectives. The transportation network is defined by the customers' locations, geographical location of the shipments, check points locations, distances between the production facility and the different check points, and distances between the check points and the customers' locations. The objective function is to minimize the in-transit related costs, which are comprised of the below costs:

- Disposal cost for the items perished during transportation composed by the items production cost (raw material, machine use, labor, energy, etc.) and the cost of their disposal.
- Transportation cost composed by the items in-transit cost from the production facility to the customers or to the point where a disposal decision is made.

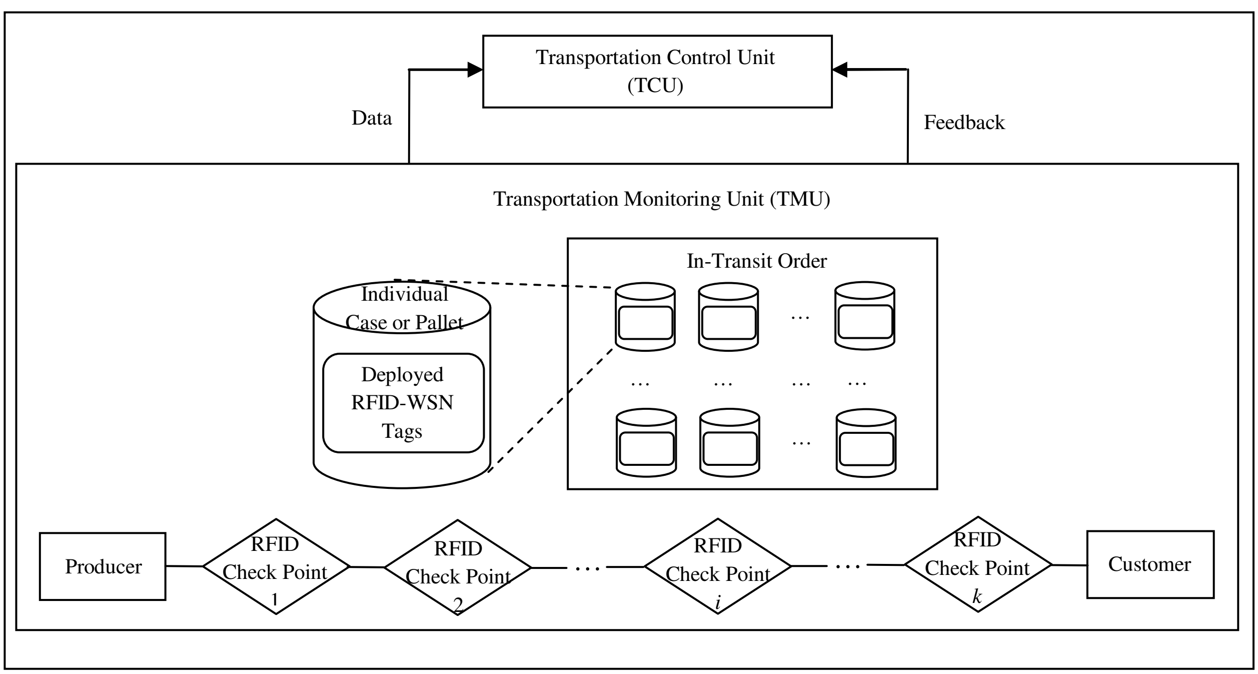

Figure 5. Internal architecture of the Transportation Monitoring and Control Unit (TMCU).

- Lost sales cost, which is non-zero when a shipment fails to reach the customer, and is composed by the lost profit and the penalties imposed by customers for not receiving the ordered items on time.

Then, the decisions to be made at the check points include discontinuing the transportation or rerouting based on the following scenarios:

- If data retrieved at any check point show that required transportation conditions were maintained, then, transportation is continued to either the next checking point or to customer location for delivery.
- If the items are already spoiled, then, the TCU stops the transportation of those items, and places a new order, corresponding to the lost shipment, with the GCU if there is still time to backorder; otherwise the customer demand is considered as lost sales.
- If data retrieved at any check point show that the required conditions were not maintained because a failure occurred, the failure time and the remaining time before items are considered perished are determined. Then, if the shipped items cannot reach the customer location, where the items were originally sent, without being spoiled, the TCU assesses the rerouting options consisting of shipping the items to another customer or returning the shipment to the production plant. This decision depends on the distances between the check point and the geographical locations of the corresponding rerouting options. If there is more than one rerouting option, the TCU will cooperate in the decision-making process with the GCU.

Considering the disposal, transportation, and lost sales costs, the optimal decisions regarding to either stopping transportation or rerouting is made at the check points by seeking results to the following problem:

MIN *In-Transit Cost = Disposal Cost + Transportation Cost + Lost Sales Cost*

SUBJECT TO: *Customer Demand*, *Delivery Deadline*, *Remaining Time to Item Spoilage*, and *Distance Between Check Points and Customers Locations*

2.4. Global Control Unit

The GCU holds a global view of both the production facility and the transportation path and network, and it serves as a cooperation unit between the PMCU and TMCU. The global unit ensures cooperation by verifying and validating all the local decisions made by the PMCU and TMCU. If verified solutions comply with the GCU objective function, then the decisions are validated and feedback that include the approval of the corresponding decisions is sent, otherwise the decisions are not validated and the sent feedback includes also the new obtained solution. Cooperation is needed in several operational situations such as to: select among many rerouting options, place new orders for lost shipments, meet customer deadlines by verifying production and transportation times, etc. The objective function considered by the GCU considers the minimization of the overall cost. Adequate decisions can be made by finding solutions to the following optimization problem:

MIN *Total Cost = Production Cost + In-Transit Cost*

SUBJECT TO: *Production Constraints* (*Customer Demand*, *Delivery Deadline*, *Machine Availability*, *Preventive Maintenance Operations*, *Inventory Restrictions*, and *Labor Availability*), and *In-Transit Constraints* (*Customer Demand*, *Delivery Deadline*, *Remaining Time to Item Spoilage*, and *Distance Between Check Points and Customers Locations*)

3. Conclusions and Future Work

This paper proposes a framework for the design and implementation of a monitoring and control system for production and transportation operations. The proposed system is intended to provide more flexibility and agility in the face of uncertainties inherent during operations through the use of autonomous and cooperative units. Future work will include designing and implementing a simulation model for the proposed system that will define the limits for autonomy and cooperation between the units and investigate the benefits of the proposed architecture in improving the enterprise operations.

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