Aluminium Electrolysis Cells: Anode Changing Automation Challenges

Antonio Pucci[1] and Alexis Guevara Melendez[2]
1. Chief Advisor, Rio Tinto – Office of the Chief Scientist, Montréal, Canada
2. Director Automation, Rio Tinto Aluminium, Montréal, Canada
Corresponding author: antonio.pucci@riotinto.com

Abstract

Anode changing in an aluminium smelter is a complex and recurring task that directly impacts the process efficiency and operating cost. In each smelter, several hundred anodes are changed every day; this process is done with a pot tending overhead crane, which is manually operated. These operations occur in extreme environments inside a smelter, including wild swings in temperature gradients, magnetic fields, process off gasses, and dust. All these elements play havoc with advanced instrumentation, sensors and machine vision equipment. Rio Tinto has experimented and trialed to automate this task over a period of four years; whilst some aspects of the task could successfully be automated, others including the most value-added tasks could not be demonstrated with adequate success rates. This work highlighted the high degree of variability of the task, the decision process made by the operator and the influence of the environment on the ability to see and sense the work to be done. This paper will present the applications, introduce the results, present the challenges and discuss potential pathways, scalability and cost challenges.

Keywords: Anode Change automation, Machine vision, Decision aids.

1. Introduction

Aluminium smelting using AP3X technology entails the operation of typically 300 electrolysis cells in series per pot line in a smelter, each of these cells having 20 carbon anode assembly's, shown in Figure 1, which consume themselves over a 27 days period. The reduction of aluminium oxide by means of the traditional Hall-Héroult process requires a carbon reducing agent to liberate the oxygen atoms thus producing pure aluminium metal.

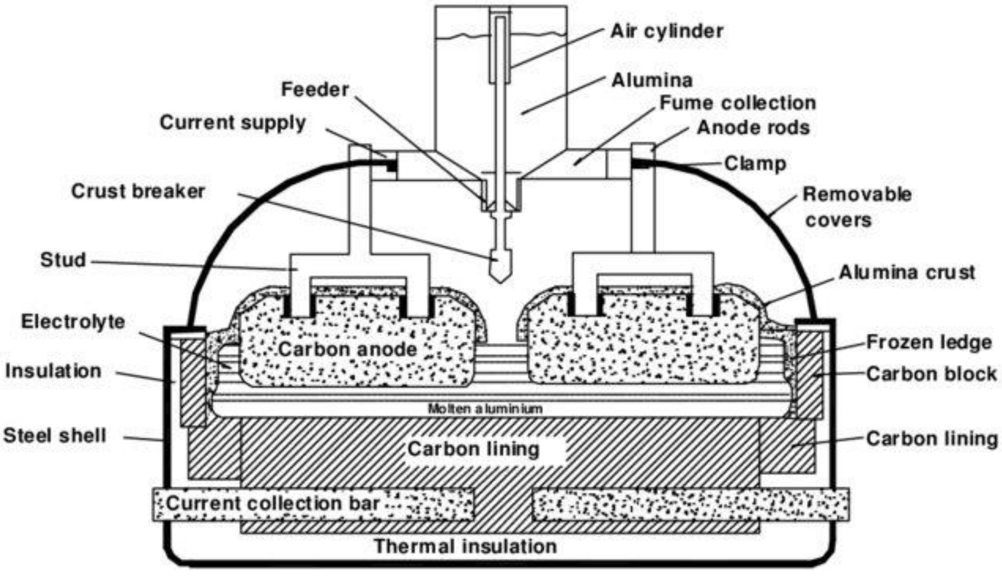

Figure 1. Typical prebake electrolysis cell cross-section [1].

In a typical aluminium smelter operation, the logistics of anode replacement occurs on an around-the-clock basis with typically one anode assembly being changed in each electrolysis cell every day. These anode assemblies are changed using a pot tending machine (PTM), shown in Figure 2, which is a highly specialized, manually operated overhead crane with its own tool suite. An anode change requires more than ten distinct activities performed by the operator with the support of a helper on the ground. Note that these activities vary from pot to pot due to specific cell conditions.

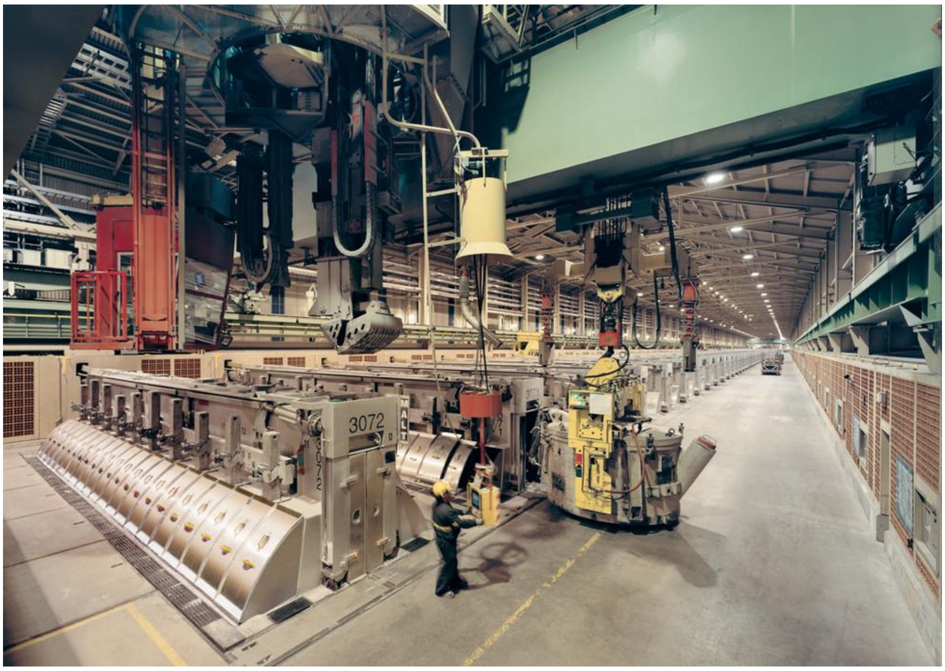

Figure 2. Typical side-by-side potroom arrangement and PTM tool tower (Rio Tinto Alma smelter).

In 2015, we have conducted a pilot program to demonstrate the possibility to automate the anode change process with advanced machine vision systems and positioning technology installed onto existing pot tending machines. The demonstration was carried out at Rio Tinto Aluminium AP-60 demonstration smelter in Saguenay, Québec, Canada. The reason behind such a choice was the possibility to have access to many enablers, which included:

- Latest-in-class WI-FI technology available;
- New equipment with minimal wear and tear;
- State-of-the-art control system with data acquisition and analysis capabilities;
- New building with minimal aging deformations and drift;
- An environment which was favorable to testing;
- An operating schedule which had the latitude to carry out industrial trials as only 19 electrolysis pots are assigned to a single crane, whereas 28 to 40 cells are typically tended by an individual PTM in full-scale smelters.

2. Purpose of Anode Change Automation

2.1 Health, Safety and Environment (HSE) Aspects

The anode change task exposes both the crane operator and operating floor handler to multiple HSE risks, currently controlled through a mix of administrative and exposure management procedures as well as personal protective equipment. These risks include:

- Exposure to process fumes containing HF and PFC gases, and fine (PM 2.5) particle dust;
- Coactivity between crane and ground operators;
- Environment with high temperature gradient;
- Thermal stress management;
- Manual handling of repetitive loads of up to 30 kg;
- Repetitive joystick operations;
- Awkward postures to obtain the right view of the task at hand.

2.2 Process Efficiency Aspects

Even though the anode change process is standardized and managed through a detailed work procedure, a high degree of variability with respect to quality and tool motions can be observed between different operators as well as different anodes changed by the same worker. A portion of this variability is due to the intricacies of the respective anode location on the electrolysis pot and the associated poor visibility of those cavities. Further sources of variability are drifting of the hydraulic system on the crane and, finally, operator's own assessment and decision process when setting each new anode.

Defects in the placement of new anodes can take between 24 and 72 hours to be noticed through the pot control system and often require a resetting intervention, which brings additional instability to the operation of the electrolysis cell. Hence, the benefit of automating this activity would ensure that each anode would be properly changed and set through a predictable and repetitive methodology, which would not be influenced by either the skills or perception of the operator. Additional expected gains include:

- Lower pot emissions;
- Improved stability of the pot thermal equilibrium;
- Improved current distribution within the pot.

These gains would translate into a more constant and potentially improved current efficiency, which is the main productivity key performance indicator (KPI) in aluminium smelting (along with specific energy consumption).

2.3 Performance Aspects

At the onset, limited KPIs were set to define the expected performance of the automation project. The KPIs targeted a prescribed number of successful anode changes per shift as well as the expected cycle time of such an anode change.

The KPI for the anode change success was set at 90 % on the premise the remaining 10 % of anode changes could be done remotely by a central control room operator who would manage the operation of four pot-tending machines simultaneously.

The average cycle time KPI for both the manual and the automated anode changes shall be the same while considering a 12 hours shift and same number of pots to tend by one PTM. The removal of time losses due to shift and breaks allows compensating for the slower nature of automated operation.

3. Automation Methodology

The approach taken by the team and the automation technology supplier (vendor) was to automate the actual task sequence the operator had to perform as defined in the standard work procedure, shown in Figure 3.

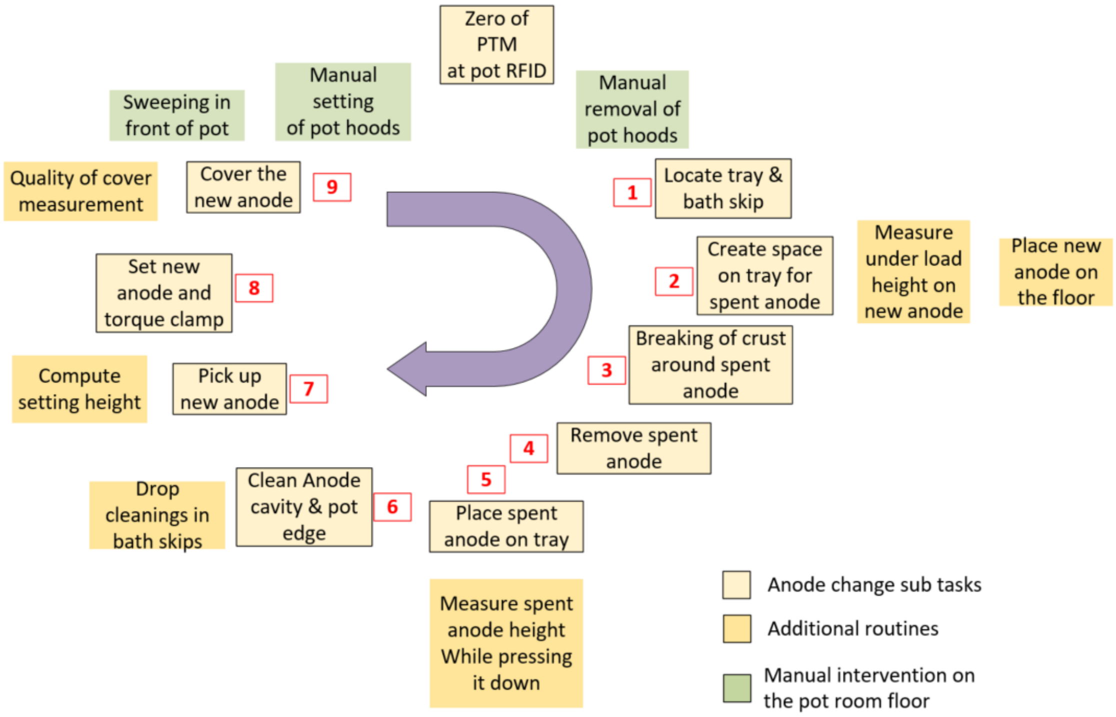

Figure 3. Anode change task cycle.

To enable automation, the crane was equipped with supplemental equipment:

- Position encoders on the crane tools;
- Computer vision cameras to assist with positioning and to monitor task completion;
- 3D camera to assess the anode covering quality.

3.1 Crane Positioning

Aluminium smelters potrooms can be as long as 1.6 km with seasonal (or even daily in some parts of the world) variations, which can be as much as 15 to 20 cm when considering the thermal expansion of the crane rails installed in the buildings. The aging of said building and the thermal cycle of each electrolysis pot also have an impact on crane positioning and travel distance to accomplish the pot tending tasks.

For this reason, positioning system location calibration radio frequency identification devices (RFID) were installed on each electrolysis cell to enable local positioning of the crane and zero in the calibration of the position encoders.

3.2 Combining Manual and Automated Tasks

To enable the anode change task, new rodded anodes and bath holding skips are delivered to the pots ahead of the anode change task. Due to the size of the trays and the narrow space of the potroom service aisle, anode trays and bath skips were delivered and grouped in clusters of three pots to be serviced along the potroom service aisle, ahead of the anode change shift. These trays and skips were delivered with man-operated vehicles and their positioning was not accurate at times, even though markings on the floor and walls were present to assist with the positioning.

3.3 Pot Tending Tasks

The automation of these tasks was carried out by coding the standard working procedure (SWP) into automation subroutines that would emulate the actions of an operator. These actions were separated into two clusters, namely, operations that are location and position based, as well as those requiring a decision-making step by the operator.

3.4 Information System

The initial system interface provided limited information feedback to the supervisory operator of the crane and the vendor did most of the data collection and interpretation. As the pilot work stretched out over almost 36 months, several iterations of improvements to the interface were made to enable proper feedback to the operator and a feedback mechanism for reporting events.

3.5 Machine Safety System

Early in the project definition, the vendor realized that no solutions to manage the machine safety aspect of the proposed automation in a dynamic environment where co-activity occurs was available. Therefore, the machine safety aspect was decoupled from the actual crane automation process and carried out by Rio Tinto along with a machine safety consultant.

The selected technology approach was through machine vision and specific personal protective equipment (PPE) color recognition. The retained primary color was green as there was nothing of green color in the potroom environment shown on Figure 4. The system was designed to manage several hundred possible security risks whilst meeting applicable machine safety protocols and codes. A scanning of the work environment and go-no-go decisions were being made every 200 milliseconds.

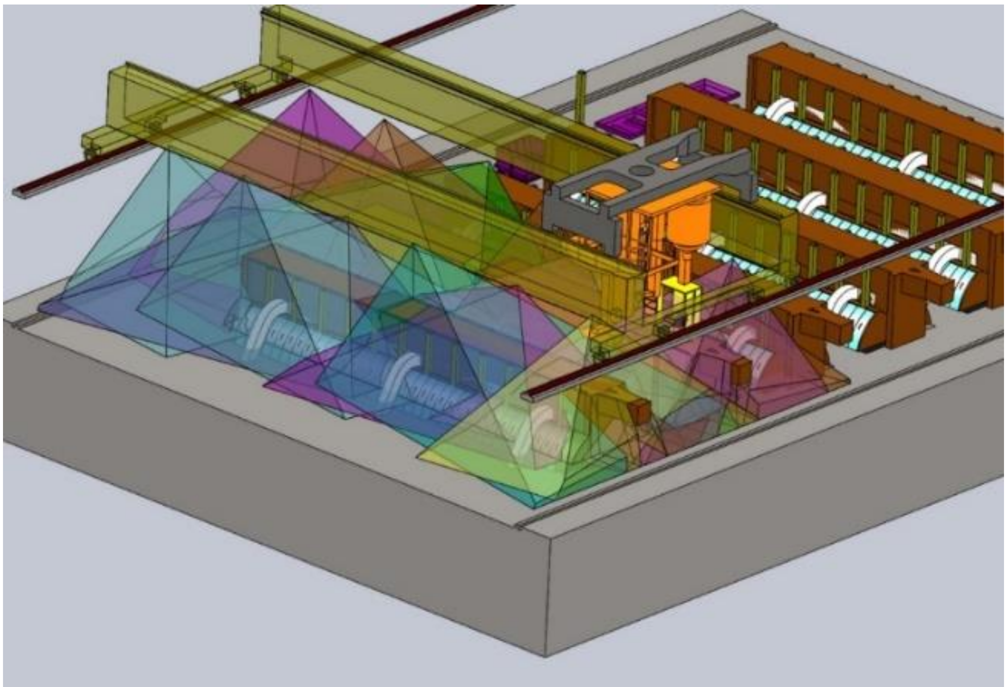

Figure 4. Scanning principle.

4. Trial Outcome

This automation trial occurred in two distinct phases. The first one, which lasted about two years was driven almost solely by the vendor and was aimed at fulfilling its own requirements and expectations from such a technology development with limited input from our operations. The later phase, which took place during the last year of trials, was managed by Rio Tinto and heavily involved the operation team of the site. This allowed to reclaim the operators' input and feedback on the then trialed system as well as required improvements to increase the performance of the technology – refer to Figure 5.

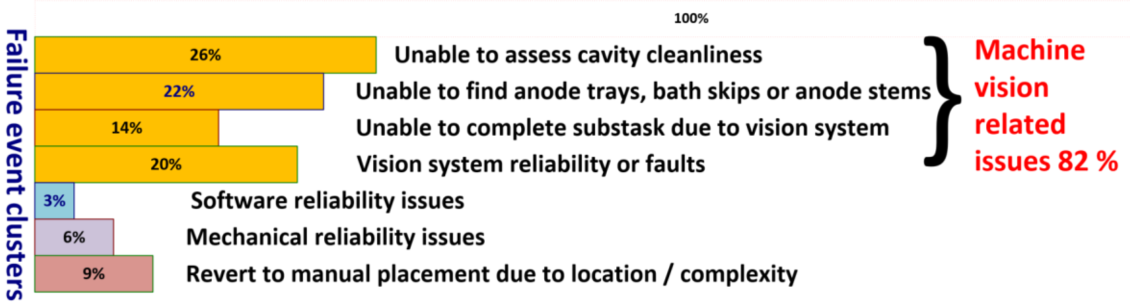

Figure 5. Failure root cause analysis.

4.1 Operation Team Experience

As soon as we brought the operation team on board, our understanding of the technology made a significant leap forward. Together we were able to get first-hand accounts of the issues and their root causes, and get a much better understanding of their contribution to the daily fulfillment of these tasks. They also brought to light various shortcuts and workarounds they have come up with while dealing with the existing equipment limitations. The insight they provided demonstrated that the SWP was not representative of the day-to-day reality and that some of the subtasks were much more complicated than expected. Finally, their knowledge of the task and the environment also allowed us to test the limits of the automation package and to identify the blind spots the technology could not manage.

4.2 Equipment Aspects

The pot tending cranes are complex machines with a mix of onboard hydraulic and motorized systems to carry out their duties. These systems tend to be complex and have varying degrees of reliability over time. The collected data during the first year of piloting highlighted more than a dozen of equipment and/or instrumentation issues that hampered the performance of the technology and the success rate of anode changes. The main issues that were identified and corrected include:

a) Deterioration of the hydraulic system flow and pressure over time, which caused automated cycles to stop. Depending on the task and the PTM tool, a series of constant flow or constant pressure control loops were developed to maintain the hydraulic system integrity, eliminate alarms and to predict maintenance interventions;

b) Position limit switches with no wiggle room: when tasks are done manually, the operator decides whether a tool is sufficiently gripping a load or if a tool is at the right resting location (even if the actual limit switch is not triggered), whereas the automated mode require these positions to be reached and confirmed. Several switches were replaced with position encoders to provide a wider spectrum of position possibilities and mimic in the automated system the flexibility the operators have;

c) Legacy mechanical components, which were maintenance intensive and thus inappropriate for automated systems. Several of the clamping mechanisms on the crane tools had to be redesigned and replaced with components suitable for heavy-duty and fatigue-intensive applications;
d) Integration of advanced automation and machine vision components used for the first time in a harsh smelter environment, which were at the limit of the supplier's experience. We also faced limited technical support, as we were trialing these technologies outside of their typical range of industrial applications, mainly focused in the manufacturing industries.

4.3 Task Fulfilment Aspects

As shown on Figure 3 above, the anode changing cycle entails the fulfillment of nine specific tasks. These tasks are divided in three major clusters:

a) After solving the bulk of the crane reliability issues, the tasks relying on positioning and actuation subsystems were the ones that have achieved the highest level of performance and quality. In some cases such as the crust breaking cycle, the new anode setting and clamping tightening results exceeded the 90 % success rate;
b) As outlined on Figure 5 above, the tasks relying on machine vision systems were responsible for more than 80 % of the failed cycles due to the inadequacy of the vision system to cope with the physical environment of a potroom (temperature, magnetic field, and lightning intensity) as well as with the often too narrow optical field of the sensors;
c) A cluster of tasks relying on human interpretation and decision was identified quite late in the piloting work thanks to the feedback from the operators. Two of the subtasks, the cavity cleaning and the anode covering, which have a material impact on the process efficiency, require the interpretation from the operator to decide if the task was done successfully. This was not understood when the project was launched.

4.4 Project Management Aspects

The vendor initially drove the pilot project. Their initial approach was to develop and test their original code and approach on their own. As the pilot continued, the Rio Tinto team took a more active role by establishing a Pareto based approach to identify and workshop issues resulting in tangible solutions. Figure 5 above outlines the progress made after almost eight months of work.

4.5 Machine Safety Aspects

The custom-purpose developed machine safety system based on machine vision and specific PPE color proved to have a limited operating life due to the environmental conditions in the potrooms. This system relied on component suppliers input, which turned out to be inaccurate when faced with the potroom reality and for which the suppliers offered little-to-no help in the resolution of the issues. Furthermore, we soon realized that a single vison server was not sufficient to properly compute the go-no-go instructions to the crane for the entire physical space of a potroom. We ended up having to install four such servers to cover each corner of the crane.

Finally, through various simulations and test trials, we realized that several dead zones with visual ambiguity were present in a potroom. These zones varied over a 24-hour period based on sun position as well as heat or magnetic field gradients.

4.6 Actual Performance KPIs

As stated above, two KPIs were considered to assess the success of such a project:

a) The anode change success rate was set at 90 % for each work shift. The actual success rate achieved over more than 24 months of piloting and based on the adequacy of such an anode change to maintain the process performance was in the low 60 %.

b) Once the bulk of the crane reliability issues was solved and that the operator practices in with respect to crane motion were implemented, the overall cycle time for a successful automated anode change was improved and reduced from 95 seconds more than that required for a manual change to only 35 seconds, as shown on Figure 6. Unfortunately, the cycle time becomes unacceptable when multiple failed attempts occur and result in almost 40 % of changes becoming unsuccessful.

Figure 6. Improvement of automated cycle time.

5. Challenges and Opportunities

5.1 Challenges

The piloting of this technology has highlighted several technical, economic and human challenges that have to be resolved if we aspire for a future adoption of such a technology in the aluminium industry. As mentioned in this paper, we have overcome a number of these challenges but, as shown in Figure 7, a number of residual issues, which could not be either technically or economically resolved, remained. We also realized that in order to find such solutions, we would need to look beyond the aluminium industry and both its traditional original equipment manufacturers (OEM) and supplier base to access viable automation products and solutions on a reasonable economic model.

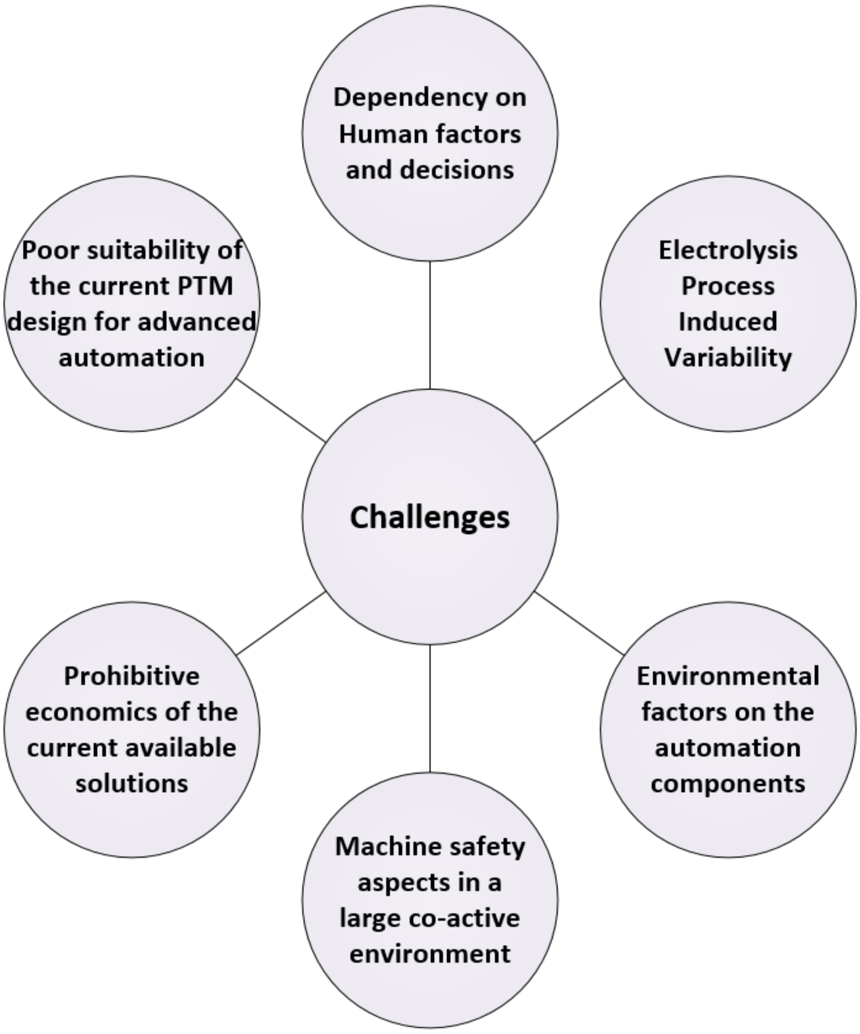

Figure 7. Challenges to the technology adoption.

5.2 Opportunities

Following the shelving of this project, we carried out a retrospective analysis of the results and reached out to several external experts to help us understand its outcome and how we could improve it in the future.

The feedback and recommendations received from these experts covered several aspects of the undertaking as follows:

a) Classify potential project candidates on a complexity and maturity scale and prioritize less complex projects when the maturity level is low;
b) Work on increasing the maturity level of the required subsystems that would enable future projects. Potential for partnerships with OEMs with suitable products and solutions for our needs;
c) Deconstruct the project in its elemental subtasks and progressively implement the successful ones;
d) Rethink and redesign the process based on automation, once the current task and its human interaction are well documented and understood;
e) Maximize the number of semi-autonomous tasks which could be implemented and that do not require the complexity of a machine safety system;

f) Take a time-proven approach, as shown on Figure 8 below, to design future projects in the automation field.

This experience has also outlined the need to look beyond conventional automation and automation technologies and to integrate the more novel approaches that include artificial intelligence (AI) to model and control the process. Such decision-based autonomous platform would be able to react to the electrolysis process variability and aim to maintain the process efficiency, which is key to the economic viability of such a technology roll-out.

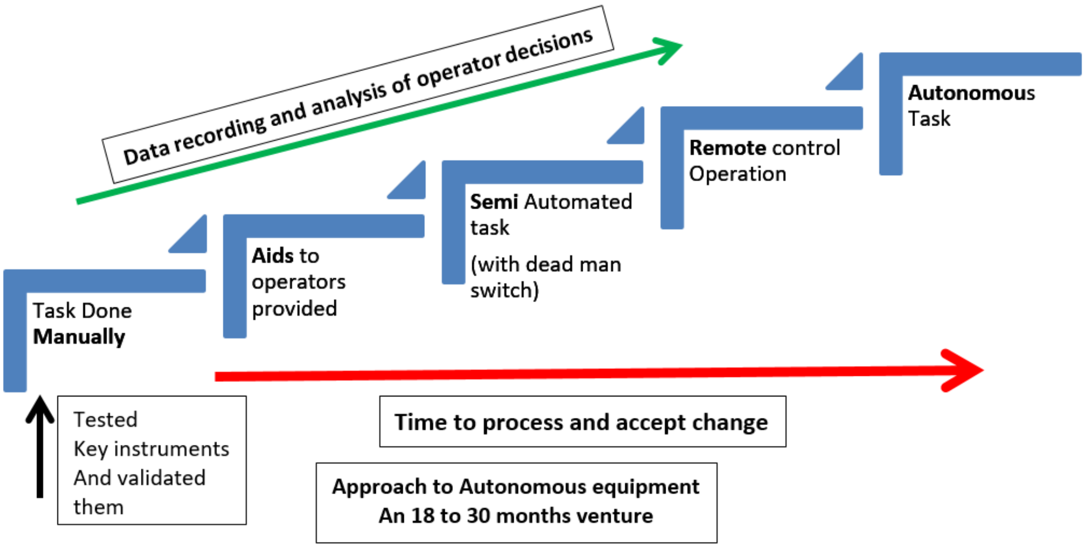

Figure 8. Proposed methodology towards autonomous operation.

6. Conclusions

This technological development trial on an aluminium smelting-related task (which was assumed to be fully understood and under control) has highlighted the limits of relying solely on standard working procedures. It also confirmed to us the hard way:

a) That we grossly underestimated the contribution of the operator to the success of the task;

b) The need to forget how we perform a given task manually and redesign it for an autonomous execution, as other industries before us (*e.g.*, automotive).

We also have to emphasize that, once Rio Tinto took over the management of the trial, the amount of effort and resources dedicated to the project increased substantially, as well as the number of external experts that were involved to help us find solutions.

Moving forward with such a technology will require open collaboration of many aluminium producers, solution providers and suppliers as the cost of building a proprietary solution will be prohibitive to any single company.

7. References

1. A.R. Burkin, *Production of Aluminium and Alumina*, Great Britain, John Wiley & Sons, 1987.