INFORMATION TECHNOLOGY

Principles of Automation for Patient Safety in Intensive Care: Learning From Aviation

Jason Dominiczak, MIT; Lara Khansa, PhD

Background: The transition away from written documentation and analog methods has opened up the possibility of leveraging data science and analytic techniques to improve health care. In the implementation of data science techniques and methodologies, high-acuity patients in the ICU can particularly benefit. The Principles of Automation for Patient Safety in Intensive Care (PASPIC) framework draws on Billings’s principles of human-centered aviation (HCA) automation and helps in identifying the advantages, pitfalls, and unintended consequences of automation in health care.

The Framework and Its Key Characteristics: Billings’s HCA principles are based on the premise that human operators must remain “in command,” so that they are continuously informed and actively involved in all aspects of system operations. In addition, automated systems need to be predictable, simple to train, to learn, and to operate, and must be able to monitor the human operators, and every intelligent system element must know the intent of other intelligent system elements. In applying Billings’s HCA principles to the ICU setting, PAPSIC has three key characteristics: (1) integration and better interoperability, (2) multidimensional analysis, and (3) enhanced situation awareness.

Recommendations: PAPSIC suggests that health care professionals reduce overreliance on automation and implement “cooperative automation” and that vendors reduce mode errors and embrace interoperability.

Conclusion: Much can be learned from the aviation industry in automating the ICU. Because it combines “smart” technology with the necessary controls to withstand unintended consequences, PAPSIC could help ensure more informed decision making in the ICU and better patient care.

Data science and analytics offer an opportunity to revolutionize how seemingly overwhelming data are processed. The tools and techniques that data analytics offers allow for real-time analysis of a vast amount of data. This data science movement has helped some organizations transition from using anecdotal reasoning to implementing data-driven decision making, which enables researchers to analyze a stream of data and provide actionable inferences in real time at scale. In the United States, national health care laws such as the Health Insurance Portability and Accountability Act (HIPAA) and the Health Information Technology for Economic and Clinical Health (HITECH) Act have ushered health care into the digital data era. With the transition away from written documentation and analog methods, the amount of observational data generated from sensors and diagnostic equipment in the clinical setting has grown exponentially. This, in turn, has opened up the possibility to leverage data science and analytic techniques to improve health care. In the implementation of data science techniques and methodologies, high-acuity patients can particularly benefit. The ICU, in treating the sickest of the sick, represents a unique part of a hospital. Because of the criticality of their health conditions, ICU patients must be closely monitored, and care is typically more intense in that it involves life-support machines. This advanced machinery generates immense amounts of vital data, ranging from heart rate and rhythm, to respiratory rate, and blood oxygen level, to name a few. Health care providers use these data to ascertain the status of their patients and intervene swiftly when abnormal readings are detected. The vast amounts of data generated by the multitude of ICU devices are hard to monitor around the clock. The most prevalent workaround thus far has been through using alerting systems that warn staff when a patient’s condition deteriorates and needs immediate attention, but the plethora of alarms of various ICU systems operating in silos has also created additional challenges related to alarm fatigue.

In the not too distant past, commercial aviation faced a similar dilemma. Aircraft consisted of mostly analog devices with no autopilot or other automation technologies. Flight engineers were essential to closely monitor the aircraft’s systems, including the engines, life support, and navigation systems, and resolving problematic conditions promptly at their onset. For the duration of a flight, they watched the multitude of gauges, adjusted knobs and levers, and used their training and experience to ensure the safety of people onboard. Automation and technological advances created safer airplanes and made their operations more reliable, albeit with unintended consequences. This fundamental transition to automation has yet to happen in health care. In this article, we report how we
drew on the aviation industry’s history of modernization and automation in developing the Principles of Automation for Patient Safety in Intensive Care (PAPSIC) framework. It draws on Billings’s principles of human-centered aviation (HCA) automation\textsuperscript{10} to help health care providers retain control and swiftly respond to failure. PAPSIC is intended to help in identifying advantages, pitfalls, and unintended consequences of automation in health care.

THE FRAMEWORK AND ITS KEY CHARACTERISTICS

HCA was developed in the early days of aircraft automation, which resulted in errors and subsequent fatalities. Attempts to improve productivity through automation does not imply less human involvement; on the contrary, it requires more active human involvement, but involvement that is better defined, organized, and streamlined—both during normal operations and, particularly, when automation fails.\textsuperscript{11} Norman has stated:

The problem is that the operations under normal operating conditions are performed appropriately, but there is inadequate feedback and interaction with the humans who must control the overall conduct of the task. When the situations exceed the capabilities of the automatic equipment, then the inadequate feedback leads to difficulties for the human controllers.\textsuperscript{12} (pp. 585)

Norman calls this feedback system a “loop” and emphasizes that the “human controller” (operator) should be at the center of the loop interacting with the system.\textsuperscript{12} Billings’s HCA principles are similarly based on the premise that human operators must remain in command, so that they are continuously informed and actively involved in all aspects of system operations. To ensure human control, Billings adds that automated systems need to be predictable and must be able to monitor the human operators; every intelligent system element must know the intent of other intelligent system elements; and automation should be simple to train, to learn, and to operate.\textsuperscript{10}

Just as a pilot is responsible for the lives of passengers onboard, health care providers are responsible for their patients’ safety while under their care. Accordingly, in applying Billings’s HCA principles to the ICU setting, we propose that PAPSIC have three key characteristics: (1) integration and better interoperability, (2) multidimensional analysis, and (3) enhanced situation awareness, as we now describe.

Integration and Better Interoperability

The plethora of monitors, pumps, machines, and diagnostic equipment in the ICU must be integrated in a centralized conduit or bus, which, in the aviation context refers to “the data highway which links one computer to another within the aircraft.”\textsuperscript{13} (pp. 191–192) A bus thus can aggregate information about the disparate system entities in one place, thus providing a complete view of the ICU operations. This would ensure that, per Billings’s HCA principles, the human agent has access to holistic up-to-date information in real time. Importantly, in our framework, interoperability is key because it is practically impossible in a highly complex and stressful ICU environment to keep track of system silos that operate on the basis of conflicting standards and protocols.

Prior to automation, aircraft gauges, sensors, and systems operated as siloed units with no integration and little interoperability, which led to duplicate alerts, prevented the system from ascertaining the status of the aircraft, and impeded the ability for automated tasks to be safely completed.\textsuperscript{10} The lack of communication, also called “strong silent automation,”\textsuperscript{14} (p. 55) has led to inadequate understandability, which lowers the system’s predictability. Bradshaw and colleagues explain that “there’s nothing worse than a so-called smart machine that can’t tell you what it’s doing, why it’s doing something, or when it will finish.”\textsuperscript{15} (p. 55) A comprehensive systematic review conducted by the Alarm and Fatigue Task Force of the Society for Critical Care Medicine emphasized alarm integration as a critical component of any successful interventions to reduce alarm fatigue.\textsuperscript{15}

We similarly advocate that for automation to be beneficial, it is necessary to ensure interoperability. The integrated ICU is meant to feature interoperable capability so that the data from all patient care devices are tied together. In this integrated ICU, all clinical monitors and devices communicate via a unified infrastructure. Such an integrated system would enable access to more comprehensive and up-to-date information, in turn improving alarm performance, reducing alarm fatigue, and enabling more informed decision making. To ensure interoperability in the ICU, Underwood and colleagues proposed two approaches.\textsuperscript{16} In the first approach, semantic annotation and processing of spatially distributed and heterogeneous sensor data are carried out on a centralized cloud, while in the second, ontologies are used to aggregate and process computational data from local sensor networks.\textsuperscript{16} Darby and Kahn similarly recommended using natural language processing to improve sepsis alerts and machine learning techniques to improve the accuracy of these alerts.\textsuperscript{17} We propose aggregating all data locally into the integrated ICU, which should interface seamlessly with the hospital’s electronic health record (EHR) system.

Multidimensional Analysis

To minimize false alarms in the ICU, we propose using a multidimensional algorithm that helps focus on a set of important parameters rather than on a single dimension that would not represent the entire system. This smart algorithm would also enable more effective decision making by screening out irrelevant information or noise and only focusing on useful information.\textsuperscript{18} As such, it would be characterized by increased specificity. It is equally important to continuously assess whether the algorithm is effectively fulfilling its role of improving alarm performance.\textsuperscript{18}

In the aviation industry, aircraft manufacturers develop systems to notify pilots of issues with the aircraft’s...
mechanical operation, aircraft traffic that may affect the current course, and terrain and obstructions in the flight path. Culminating with the Boeing 747, the number of discrete warning alarms grew considerably, which increased system complexity and resulted in data overload. Several airplane crashes have been attributed in part to the plethora of warnings that inundated the pilots. For example, the Air France Flight 447 crash in 2009 was attributed to discrepancies in the aircraft’s indicated air speed because the aircraft’s airspeed sensor was obstructed by ice and fed incorrect information to the flight management system. The automated flight director system incorrectly signaled the pilots to climb, which led to a stall and the eventual crash of flight 447.

In more recent models, aircraft designers supplemented the basic sensors with additional logic and data to suppress spurious alarms and prevent alarm desensitization.

Medical devices in the ICU such as cardiac monitors are programmed to automatically alert the nursing staff of a medical crisis with their patients. Although such alerts are necessary in a clinical environment, repeated false alarms could lower the informativeness of the alarm signal, resulting in clinicians disregarding a higher proportion of legitimate alarms. With the ubiquitous use of cardiac monitoring clinical alarm fatigue has been found to be a major technology hazard. Thus, a smarter alarm is a necessity in the future of the ICU. In one study, current electrocardiogram (ECG) monitors were reconfigured to suppress some spurious warnings, which reduced the amount of spurious or nuisance alarms, in turn improving patient satisfaction and reducing alarm fatigue. Dynamically annotated visualizations have been proposed as a replacement for traditional displays, which tend to have more intrusive alerts, which often get turned off or ignored.

Current device-specific monitoring is only able to alert health care providers on the basis of a set of predefined conditions. This inflexible system is inherently error prone, as the accuracy of the alarm is tied directly to the accuracy of the data it gathers. A current-generation ECG monitor alerts health care staff when a patient’s sampled heart rhythm shows a deadly arrhythmia—but is unable to look at the patient’s other data points for confirmation. The monitor can be “tricked” into falsely alerting the health care provider every time a patient is simply brushing his or her teeth.

Finally, predicting unstable health conditions cannot be easily accomplished by solely monitoring stand-alone symptoms. Instead, increasing data dimensionality allows for more informed decisions based on several important parameters that exist concurrently and that need to be monitored in tandem to effectively assess overall health. The higher the concurrency of the data fed to an algorithm, the faster and more accurate the detection of a critical event.

Enhanced Situation Awareness

PAPSIC would also offer enhanced situation awareness capabilities and an integrated personalized display that serves as a real-time system dashboard of all system functionalities. It is also equally important that the automated system be designed to increase the operators’ situation awareness, which generally signifies “knowing what is going on around you” and implies remaining “coupled to the dynamics of the environment.” In aviation, situation awareness is akin to an “internalized mental model of the current state of the flight environment.” Most aviation crashes, such as the crash of the previously mentioned, Air France 447, can be attributed to a loss in situation awareness.

To improve situation awareness in the ICU, the medical industry should follow the aviation industry’s push to use integrated displays. Anders et al. proposed IGID, an integrated graphical information display that proved superior to the traditional tabular display in boosting nurses’ ability to detect abnormal patient vitals. Similarly, Koch et al. showed that information integration in displays improves nurses’ situation awareness, while simultaneously reducing task completion time.

RECOMMENDATIONS

We now provide the recommendations, as summarized in Sidebar 1, for health care professionals and vendors to facilitate PAPSIC’s application to the ICU.

**Health Care Professionals**

Implementing automation in the ICU environment is a positive change that will nevertheless introduce new challenges以至于导致重大航天器事故。“膨胀的 ’ 航空安全 ’ 不断出现的警告信息导致系统疲劳。”

**Sidebar 1. Recommendations to Health Care Professionals and Vendors**

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<td>More skilled professionals</td>
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<th>Vendors</th>
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* References can be found on pages 000–000.
in the event of overreliance on automation. Rather than completely relying on automation, health care professionals should make automation work for them by ensuring that the joint human-agent system is “mutually predictable” and “mutually directable” and maintains “common ground.” Otherwise, complete reliance on automation could cause potentially severe problems because of unevenly distributed workload, extraneous attentional and knowledge demands, breakdown in awareness, and preparedness to automation surprises, as well as the need for additional coordination and new approaches to training, the potential for previously unobserved errors, and undue trust in automation.

An example of cooperative automation, as discussed by Cook and Woods, can be found in the use of computer-assisted continuous infusion, in which drug flow is adjusted on the basis of an external signal—in this case, the patient’s blood pressure level. For Cook and Woods, the success of automation depends on “understanding the relationship between human expertise and automation.”

CONCLUSION

The ICU is currently at a state similar to that of the aviation industry when it embraced automation, so that much can be learned from its experience. In an environment like the ICU, automation should be used with the understanding that, as aviation has learned, it is not a proverbial silver bullet. Existing ICU automation models have been built and implemented in small-scale tests but they are simplistic and do not take into consideration the requirements of interoperable systems. Because it combines “smart” technology with the necessary controls to withstand unintended consequences, PAPSIC could help ensure more informed decision making in the ICU and better patient care.

Conflicts of Interest. Both authors report no conflicts of interest.
REFERENCES


