Proceedings on Automation in Medical Engineering
Proc AUTOMED, 2026, Vol. 3, No 1, Article ID 2494, 2 Pages

Infinite Science Publishing

Safety assurance of a head-foot steered wheelchair via structured STPA decomposition

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Abstract: This work applies Systems-Theoretic Process Analysis (STPA) as an initial step toward the safety assurance of a wheelchair equipped with a head-foot steering interface designed for individuals with severe motor impairments. Modeling the system's control structure—particularly the human–machine interaction—is challenging and often leads to cascaded control loops that make the analysis time-consuming and susceptible to oversight. To address this complexity, we propose separating the analysis into two complementary parts: a human-centric loop that examines user behavior, and a computer-centric loop that focuses on sensors, actuators, and control logic. This division preserves critical human interaction considerations while streamlining the safety assessment and supporting a more robust design of the wheelchair system.

I. Introduction

This paper presents preliminary results of applying the System-Theoretic Process Analysis (STPA) to a human-operated assistive healthcare system, namely a powered wheelchair with a head-foot steering system for children with severe motor impairments. Safety in such assistive technologies is critical, but traditional hazard analysis methods focusing on component failures are inadequate to address the complexity of human-machine interaction.

STPA has been applied to many systems. When it was used for human factors analysis, most prior work involved systems with trained operators (e.g., automotive [1], aerospace [2]). In contrast, this study examines assistive technology used by children with severe upper-limb disabilities who typically lack formal training. The wheelchair is controlled via four configurable input pads: three for head movements and one for foot, providing commands such as speed up/slow down, left and right steering, and direction change [3]. For simplicity, the input pads are treated as black boxes in this analysis.

II. STPA analysis of the wheelchair

STPA consists of four steps [4]: (1) define analysis purpose by identifying potential losses and hazards, (2) model the system as a control structure, (3) identify unsafe control actions (UCAs), and (4) determine loss scenarios and causal factors. These steps address system- and controller-level constraints, enabling proactive risk mitigation during early design stages, including the concept phase, thereby enhancing overall safety.

II.I. Step 1: Defining the purpose of the analysis

STPA can address diverse objectives such as safety, security, and mission assurance. This work focuses on safety, while also considering 'loss of mission' to prevent a wheelchair user from being stranded. The defined losses are:

- L1: Loss of a human life or injury to people.
- L2: Loss or damage to the wheelchair.
- L3: Loss of mission (wheelchair becomes faulty and stops moving).

The identified hazards are:

- H1: Unintended acceleration or deceleration of the wheelchair [L1, L2].
- H2: Unintended steering of the wheelchair [L1, L2].
- H3: Loss of braking [L1, L2, L3].
- H4: Loss of propulsion [L3].
- H5: Loss of steering [L1, L2, L3].
- H6: Tipping over of the wheelchair [L1, L2, L3].
- H7: Wheelchair drives over other people's feet or bumps into other people [L1].
- H8: User falls out of the wheelchair [L1].

II.II. Step 2: Model control structure

Modeling the control structure is challenging, depends heavily on system interfaces, dependencies, and analyst expertise, and often requires multiple iterations. The final structure in Figure 1 includes two main controllers: the user with a simple mental model and the wheelchair controller with a process model, plus controllers for input pads, propulsion, and braking. The controlled process represents the physical wheelchair and its environment. Because the structure uses cascaded loops, later STPA steps, especially Step 4, can be time-consuming. To streamline the analysis and focus on the user's unique characteristics and interaction with the system, we divide it into two parts:

Human-centric control loop: Focuses on human-machine interaction aspects, examining how users will interact with the system. Insights from this analysis can inform safety requirements, user manuals, training programs and usability improvements. This control loop is particularly significant given that the primary users of the system are children with severe motor impairments.

Computer-centric control loop: Addresses technical components such as sensors, actuators, and software logic. It analyzes how control algorithms process head and foot inputs, manage speed and direction, and ensure safe operation under varying conditions. Results can guide the development of a safer and more reliable system architecture.

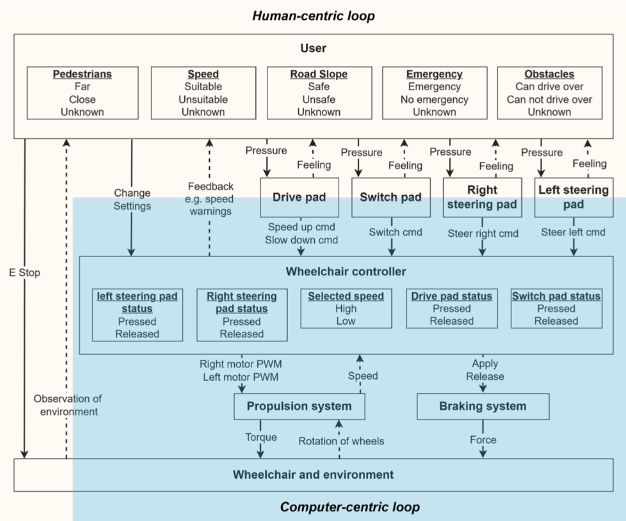

Figure 1: Control structure of a wheelchair equipped with a head-foot steering system.

II.III. Step 3: Identifying unsafe control actions

This step focuses on defining UCAs. This can be done using the following template UCA-xx: <Source> <Type> <Control Action> <Context> [link to hazards].

Example from the human-centric control loop: UCA-01: <The user> <provides> <pressure (to drive)> <when the slope in front is unsafe (greater than the manufacturer’s rated limit)> [H3, H7].

Example from the computer-centric control loop: UCA-02: <Wheelchair controller> <provides> <Motor PWM> <when the drive pad is released> [H1].

II.IV. Step 4: Identifying loss scenarios

This step identifies loss scenarios and their causal factors using the formal scenarios approach [5], which aims to ensure completeness of the analysis. The scenarios are grouped into four classes: Class 1, scenarios related to unsafe controller behavior; Class 2, scenarios related to unsafe feedback or information to the controller; Class 3, scenarios related to unsafe control execution; and Class 4, scenarios related to unsafe process behavior.

Class 1 would be formulated as follows:

- Output: <Controller> provides <Control Action> when <Context>

- Input: <Input> correctly showed that <Context>.

For UCA-01, class 1 scenario would be:

- Output: <The user> <provides> <pressure (to drive)> <when the slope in front is unsafe (greater than the manufacturer’s rated limit)>.

- Input: <User observation of the environment> correctly showed that <there is a slope ahead>.

For this example scenario, the causal factor is that the user perceives the presence of a slope ahead but continues driving because they cannot accurately assess whether the slope is safe. A potential high-level solution is to equip the wheelchair with sensors that measure the slope and prevent movement on unsafe inclines.

III. Results and discussion

The preliminary STPA analysis identified critical losses and associated hazards. Dividing the control structure into two parts, user interaction and technical safety, enhanced clarity and facilitated a more focused examination of human-machine interaction and technical aspects. However, its impact on overall analysis efficiency remains uncertain and will be evaluated in future work. Completeness will be ensured by rigorously applying Step 4 of the STPA process.

IV. Conclusions

This study presents initial STPA findings for a powered wheelchair with a head-foot steering system. The proposed approach simplifies the control structure and provides a foundation for continuing the analysis.

ACKNOWLEDGMENTS

Part of this research has received funding from the European Union's Horizon Europe research and innovation program under the Marie Skłodowska-Curie grant agreement No 101169197. Part of this research has received funding from the Research Foundation Flanders (FWO) under grant no. 1S17123N. This publication reflects only the author's view exempting the European Union from any liability.

AUTHOR’S STATEMENT

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors’ institutional review board or equivalent committee.

REFERENCES

[1] O. Hans, K. Radlak, and J. Adamy, “Human-Factor Focused Application of STPA to Remotely Driven Vehicles,” in *2024 IEEE World Forum on Public Safety Technology (WFPST)*, May 2024, pp. 120–125, doi: 10.1109/WFPST58552.2024.00026.

[2] N. A. Basnight, “The Use of System Theoretic Process Analysis (STPA) onNovel Tiltrotor Aircraft to Prevent Mode Confusion,” Thesis, Massachusetts Institute of Technology, 2025. Accessed: Dec. 02, 2025. [Online]. Available: https://dspace.mit.edu/handle/1721.1/158856

[3] “KU Leuven spin-off launches smart wheelchair,” Nieuws. Accessed: Dec. 02, 2025. [Online]. Available: https://nieuws.kuleuven.be/en/content/2021/ku-leuven-spin-off-launches-smart-wheelchair

[4] N. G. Leveson and J. P. Thomas, *STPA Handbook*, Cambridge, MA, MIT Press, 2018.

[5] J. Thomas, “STPA Step 4 Building Scenarios: A Formal Scenario Approach,” MIT Partnership for Systems Approaches to Safety, 2024. [Online]. Available: https://psas.scripts.mit.edu/home/wp-content/uploads/2024/STPA-Scenarios-New-Approach.pdf ”.