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The 4D LINT Model of Function Allocation: Spatial-Temporal Arrangement and Levels of Automation

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Abstract. Human factors researchers are well familiar with Sheridan and Verplank's (1978) 'levels of automation'. Although this automation dimension has proved useful, the last decade has seen a vast increase of automation in different forms, especially in transportation domains. To capture these and future developments, we propose an extended automation taxonomy via additional dimensions. Specifically, we propose a 4D LINT representation for vehicle operation regarding control across multiple simultaneous dimensions of (1) Location (from local to remote), (2) Identity (between human and computer), (3) Number of agents (degree of centralization of control), as well as (4) adaptive optimization over Time. Our model aims to provide guidance and support in communicable ways to allocation authority agents (whether human or computer) in optimized supervisory outer loop control of complex and intelligent dynamic systems for more efficient, safe, and robust transportation operations.

Keywords: Human factors · Functional allocation · Supervisory control
Control optimization · Levels of automation · Human-machine interaction
Human systems integration · Systems engineering · Unmanned aerial vehicles
UAS traffic management · Automated driving · Autonomous vehicles
V-2-V, Vehicle-to-Vehicle · V-2-I, Vehicle-to-Infrastructure
V-2-X, Vehicle-to-Everything · Tele-operated driving

1 Introduction

Models and frameworks for human-automation interaction and the design of control systems have the potential for longstanding impact to widely shape and direct advances in fields such as intelligent transportation systems. Seminal man-machine systems research [1] described ten levels of automation (LoA) ranging between full human control and full automation control. Multiple frameworks issued by major governmental and professional societies have recently translated such LoA concepts into LoDA (Level of Driving Automation). The German Federal Highway Research Institute (BASt)

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defined five LoDA [2]; the US DOT National Highway Traffic Safety Administration identified their own five LoDA [3], and the SAE International defined six LoDA [4].

Far from being finalized, over time these frameworks have been updated and broadened. SAE International released a revision with a substantial expansion of rationale, examples and explanatory material; for example, the explicit consideration of operational design domains [5]. In the academic realm, similar evolutions of LoA models have also been growing towards greater dimensionality. The allocation of work between humans and computers was extended by [6] to also account for four different stages of information processing: sensory processing, perception/working memory, decision making, and response selection. Further extensions by [7] were argued for beyond the previous concepts that they identified as being too coarse-grained and unidimensional and presented further modeling of task details. In 2005, a Human Factors and Ergonomics Society panel was convened around a theme of perceived unrest and dissatisfaction with simple LOA schemes from the past. In their position statements from the panel, Sheridan advocated the utility of his LOA to “get people thinking”, and Parasuraman offered that “empirical studies point to the value of variable or flexible LOA, in contrast to a fixed LOA” [8]. As a common thought experiment, comparisons to a long history of trials and tribulation of humans and automation in the Aerospace domain are often used to reflect on recent developmental pushes in automated and autonomous Automotive driving (e.g., the case-in-point name of the Tesla “Autopilot”). Notably, the evolutionary path in Aerospace has included additional dimensions regarding where a control agent was located (e.g., remotely piloted aircraft) and how many agents were in control (e.g., pilot crew team sizes).

2 Model

The task of operating a vehicle is represented along three orthogonal dimensions and optimized across a fourth, resulting in an expanded functional allocation solution space-time model (Fig. 1). The three spatial axes are the location of the control agent relative to the vehicle (1), the identity of control residing with a human or computerized source (2), and the numeric degree of centralized control obtained by dividing the number of vehicles by the number of agents (3). The fourth dimension characterizes movement of the point of control authority over time such as in outer-loop supervisory control adaptation (4). While the second axis of control identity has historically been bounded by human/computerized extremities and discretely divided, we present the remaining axes as ranging across unbounded continua. Thus, arranging these axes depicts a 4D functional allocation solution space-time model for an agency’s Location, Identity, and Number over Time (LINT). Although applicable to any transport operation (across air, space, land, or sea), we aim to introduce this concept via recounting more familiar/established cases in Aerospace towards potential outlook for new and presently emergent possibilities in Automotive applications.

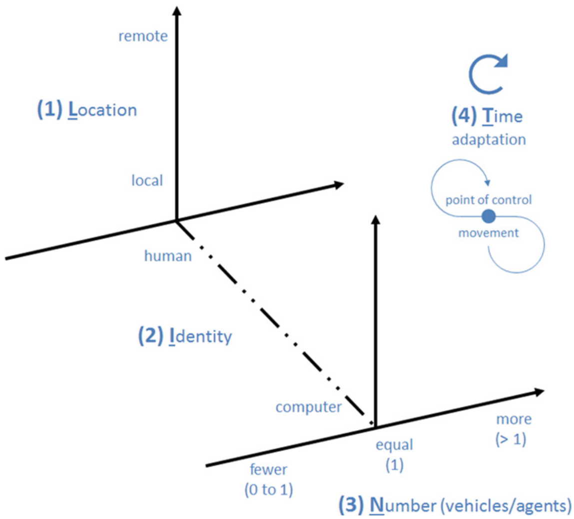

Fig. 1. The LINT solution space-time model of vehicle control functional allocation regarding dimensions of Location, Identity, and Number revolving across Time.

The LINT model can support a notation scheme to communicate concepts in a standardized way. Dot delineation can indicate which levels of each of the three spatial axes (i.e., Location, Identity, and Number) are considered in respective order and by use of a single value or range of values, it can be conveyed if a specific dimension is fixed or variant over the time dimension. For example, current day manual driving would be 1.1.1 (i.e., an agent that is respectively local, human, and singularly in control of one vehicle without time adaptation). An autonomous driving pod (e.g., "Google car") would be 1.5.1; while movement of control between SAE LoDA across time would span a range along the human-computer identity axis as 1.1-5.1. Adaptive shared control for a single vehicle between a pair of localized agents (one human and one computerized) would be 1.1-5.1/2. Example adaptive levels of tele-remote driving (e.g., in-vehicle, in-line-of-sight, beyond-line-of-sight) with a single human operator and single vehicle would be 1-3.1.1; whereas if supported by various computerized aid would be 1-3.1-5.1; and if also allowing for a remote team of several human operators would be 1-3.1-5.1/1-3. A remote highly centralized autonomous full city cloud control concept could be represented as 2.5. (1−100000)/(1−1000) (i.e., supporting up to 100000 vehicles with a ranging network of up to 1000 off-board computers).

From a LINT model perspective, a sizeable proportion of automotive attention [2–5] is mostly devoted to one line parallel to the (2) Identity axis, at a single midpoint of the (3) Number axis and at the local end of the (1) Location axis (i.e., concerning a 1:1 vehicle to agent ratio of a localized agent). Along such a single line, with varied human-computer identity (2) at different points in time (4), a majority of openly disseminated automated/autonomous driving functional allocation concepts are represented, while still being limited to the same position as manual driving along our remaining two axes (1) and (3). Across the expanded area provided by the 4D LINT model, Table 1 illustrates further control concept solution examples derivable and comprehensible from incorporating the support of the other two dimensions.

Table 1. Example explorative control concepts from Aerospace and Automotive spanning representative regions of the 4D LINT solution space-time model.

Quadrant region	Aerospace example	Automotive example
(a) Multiple local humans in single vehicle, no/little automation	Vickers VC10 jet airliner with Captain, Co-Pilot, Navigator, and Flight Engineer	Driving instructor(s) with redundant controls available from passenger/back seat(s)
(b) Multiple local computers in single vehicle, much/full automation	Cormorant/AirMule VTOL UAV with Flight Management System (FMS), Flight Control System (FCS), and Vane Control System (VCS)	Different on-board software applications conducting separate components of driving task (smartphone, tablet, etc.)
(c) Multiple remote computers operating a single vehicle	BADR-B satellite with highly autonomous ground station control in UK and Pakistan	V2I, smart city/highway concepts with dominant infrastructure authority
(d) Multiple remote human operators for a single vehicle	RQ-4 Global Hawk aircraft with 3 ground pilots: launch-recovery, mission control, and sensors operation	Team of tele-remote drivers coordinating sub-tasks of driving responsibility
(e) Single remote human operating multiple vehicles, no/little automation	Small package UAV deliveries by remote human operator	Parking garage office attendant valet service
(f) Single remote computer operating multiple vehicles	Lockheed Martin Vehicle Control System VCS-4586	Centralized traffic flow across a controlled urban or highway network
(g) Single local computer operating multiple vehicles	Autonomous formation flying with a designated lead aircraft, Georgia Tech ¼ Piper Cubs × 3	Truck platooning, computer leader with automated followers
(h) Single local human operating multiple vehicles, no/little automation	1940 Australian Brocklesby mid-air plane adhesion, piloted safely by Leonard Fuller	Truck platooning, human leader with physical tow-bar (low-tech) followers/trailers
(i) Adaptive, Adaptable allocation authority optimization	F-16 Auto-GCAS (Ground Collision Avoidance System)	Driver state monitoring (attentive eyes, healthy heart, etc.) in transitions of control

In addition to supporting thought-experiment explorations across the theoretical regions available within the 4D LINT model (Table 1), practical solutions can be predicted as emergent concepts upon consideration of specific real-life operational constraints/aims. For example, while present day automotive artificial intelligence has not yet reached the same robust flexibility for problem recognition/solution as human drivers, an autonomous car might defer to a remote human agent upon reaching an uncertain situation requiring human oversight without burdening on-board occupants, thus allowing them to retain the coveted role of passenger rather than responsible agent. A specific case suggested by Nissan in their "Seamless Autonomous Mobility" concept is that of the inability of a near-term autonomous car to interpret and execute rule-breaking behavior such as road construction workers deviating traffic to cross slowly to the opposite side of the road, beyond double-line boundaries, and in spite of a red traffic light signal [9]. A smaller set of remote human agents operating from an off-site office call center might thus support periodic on-demand cases to enable a wider fleet of on-road autonomous vehicles expand their operational domains. Within the 4D LINT model, this solution is represented for a single vehicle as a point of control movement from a 1.5.1 (local computer) to a 3.1.1 (remote human) instantiation, or as a 1-3.1-5.1 time variant adaptive concept. For a larger fleet of multiple vehicles and a smaller network pool of remote on-demand operators, the last numerical dimension in the notation scheme would reflect centralized control concepts defined in accordance with terms of specific capacity sizes.

3 Discussion

A key value of the expanded solution space of our LINT model is to cohesively structure and communicate alternative paths and flexibility in terms of functional allocation design and implementation strategies. This value is felt especially relevant and timely to research and development during periods of post-peak technology attention, visibility, and energy. Collectively known as a "hype cycle", a stereotypical pattern of activity surrounding new technology progresses first from a trigger point, upwards through a rapid peak of inflated expectations, then succumbs into a trough of disillusionment before a more gradual climb towards a steady production/penetration plateau [10]. Greater interactive dimensionality such as afforded by our LINT model draws a broader map of opportunities to explore for the potentially lost/stuck system control concept designer and human systems engineer.

Regarding a potential mapping of problem space to the our modeled solution space, the question of what either (hu)man or machine can do better than the other has been previously directly raised and addressed in seminal work commonly referred to as Fitts' List [11]. Similar constructs of tradeoffs along the remaining dimensions of the LINT model beyond human-automation agent Identity are not difficult to imagine for Location, Number and Time. To begin with, local agents have more direct access, whereas remote agents are better positioned for a broader "big picture" view. Higher numbers of agents than vehicles increases robustness through redundancy, whereas fewer agents can reduce coordination/communication lags, improve efficiency and cut costs. Adaptive/adaptable control systems are more agile and capable despite high entropy (dynamics and uncertainty) task environments, whereas fixed control systems afford greater transparency (predictability and comprehension) and parsimony. Thus, akin to the aforementioned control agent identity axis exploration provided by Fitts' MABA-MABA (Men Are Better At, Machines Are Better At) perspective; additional lists are conceivable: LABA-RABA (Local Agents Are Better At-Remote Agents Are Better At), FAVABA-MAVABA (Fewer Agents than Vehicles Are Better At-More Agents than Vehicles Are Better At), and ASABA-FASABA (Adaptive/Adaptable Systems Are Better At-Fixed Allocation Systems Are Better At). Such lists all share utility in the provision of generating guidance towards allocation authority arbiters (whether human or computerized). Such functional allocation lists for outer-loop supervisory control optimization may be understood as analogous to and in complement to the modes of adaptive parameter settings for inner-loop direct control [12].

4 Concluding Remarks

The principal motivation for the 1978 Sheridan LoA has been identified as to clarify that (the question of) automation is not an either-or (answer) [13]. Our four-dimensional LINT model also aims to illustrate available additional alternatives, especially as may presently become fruitful for the Automotive domain akin to historical developments and breadth of operations as can be seen across the Aerospace domain.

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