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The Nexus of Translational Action

Short Paper

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Abstract

Sensors, actuators, and controllers are digital objects fundamental to automation-intensive industries such as transportation, manufacturing, and energy. As technologies that enable and arbitrate the transition from physical to digital worlds, they are increasingly pervasive in all facets of industry and logistics, consumer technologies, or even medicine. Hybrid digital objects with physical and digital components are composed of bitstrings that are inscribed onto a material bearer. Translational action refers to how bitstrings are accessed in the material bearer or how they are moved from one layer of the bearer to another. We perform an inductive study of 170 sensing, computational, and imaging technologies originating from leading scientific research institutions to better understand the nature of translational action. Across four physical and digital configurations, we identify seven forms of translational action. The findings offer insight into cybernetic control theory central to automated systems to understand the nature of their logic, processes, and interdependence.

Keywords: Translational action, sensing, actuation, automation, cybernetic control

Introduction

As digital objects are increasingly infused in the everyday lives of most people, they have evolved from a class of technologies designed to facilitate the administrative efficiency of bureaucratic organizations to a broad range of computational devices that sculpt and mediate our daily reality (Baskerville et al. 2019; Recker et al. 2021). Such digital objects are designed to purposefully sense, respond, and actuate in the physical world, with increasing material agency and autonomy (Leonardi 2010). Robots, autonomous vehicles, or facial-recognition software perform both cognitive and physical actions typically associated with humans. They quietly register and store biometric and behavioral data, augment sensory perceptions, or supplant human agency in semi- or fully-autonomous systems (Yoo et al. 2010).

Interaction with the physical world requires the ability to sense, detect, infer, compute, and actuate, typically enabled by an infrastructure of connectivity and control (Siegel and Krishnan 2020). It is a larger category of technology often called “Deep Tech” (Chaturvedi, 2015; Siegel and Krishnan 2020; Romasanta et al. 2022), referring to this class of enabling technologies that function in larger industrial systems that power the industrial Internet, enable modern aviation, or control energy generation and distribution smart electrical grids. These technologies are also growing in the consumer devices such as wearable sports technologies or closed-loop drug delivery systems in medicine. Even mundane everyday objects have embedded computing capabilities that augment interaction with the user or environment (Yoo 2010). In 2016, more than 20 billion devices were connected and leveraged more than 50 billion sensors (Zhang et. al 2016).

However, as digital objects that arbitrate the interaction between the physical and digital world, they have received limited attention in IS research (von Briel et al. 2018; Kyriakou et al. 2017). As more and more sensors, actuators, and controllers are combined in complex automated systems with sub-systems and layers that can interact in unexpected ways, the need to understand how modifications at one point affect a holistic system becomes exponentially challenging and critical. This message was clearly stated in the investigations of the Boeing 737MAX crashes, where the addition of a relatively minor software module in the MCAS flight correction system prevented pilots from operating the aircraft with disastrous consequences (Federal Aviation Administration 2020).

As automation and ubiquitous computing increase, appeals have been made to reorient the IS discipline to the nexus of the physical and digital in the realm of conceptual modeling (Recker et. al 2021), venture creation (von Briel et al. 2018), or community design patterns (Kyriakou et al. 2017), but less attention has been awarded to understanding how digital objects enable this mediation or *translational action* (Faulkner and Runde 2013, 2019). Digital objects are composed of bitstrings which are "inscribed onto, contained within, or borne by a material object of some kind" (Faulkner and Runde 2019 p.8), referred to as *bearers*. Material bearers allow the bitstring to be "accessed—to be used, stored, passed to others" and to mediate with the physical world (Faulkner and Runde 2013, 2019 p.10). Translational action refers to "practices associated with movement from one layer of the bearer to another" (Faulkner and Runde 2013, 2019 p.10). Yet, what is not well specified—neither conceptually nor empirically—is a concrete and specific understanding of what translational action actually is. Consequently, we ask:

- *What are the functions of the translational actions that digital objects perform?*

Accordingly, we direct our focus on the sensors, detectors, actuators, controllers, and computational technologies that function at the nexus of the digital and physical to better understand a broad range of translational action. We address this research empirically through an analysis of 170 digital objects that transfer some form of energy[1] to bit strings, bit strings to some form of energy, one form of energy to another, or manipulate bitstrings. Our data come from a study of projects emerging from the major scientific research infrastructures in Europe that develop these deep technologies (Romasanta et al 2021, Wareham et al. 2022). Research in the natural sciences is focused on measuring some physical phenomena and deriving data and knowledge from the measurements. As such, large scientific research infrastructures have been pioneers in the development of detection and instrumentation technologies where the translation of some form of physical energy to data is their exclusive function. Additionally, they are leaders in the computational technologies needed to process and analyze such data, as well as autonomous systems required for the operation and control of their complex infrastructures. As such, the sample of 170 projects originating exclusively from these research centers offers a unique opportunity to study the nature and function of technologies at the nexus of translational action.

Our research responds to the numerous calls for greater engagement with the IT artifact to move beyond naïve conceptualizations; where the IT artifact is under-theorized, "either absent, black-boxed, abstracted from social life, or reduced to surrogate measures" (Orlikowski and Iacono 2001p. 130). Empirically, we contribute to a better understanding of the technologies of automation and cybernetics, the industrial internet, and IoT, where the interaction with the physical world is their principal function. Theoretically, our focus contributes to considerations of digital objects as both material and digital in nature (so-called hybrids) (Faulkner and Runde 2019, Pujol Priego and Wareham forthcoming) as well as calls for conceptual models focused on the mediation between physical and digital realities (Recker et al. 2021; Yoo 2010), and ontologies that embrace the dual, interdependent, or fused essences of the digital and physical (Baskerville et al. 2020; Faulkner and Runde 2019).

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[1] By energy, we refer to the broad class of energies which include thermal, kinetic mechanical, electromagnetic, and chemical.

Background Literature

The two main research streams where we position our research are the literature on translational action and ontologies. We briefly discuss both in turn.

Translational action

Faulkner and Runde define digital objects as bitstrings that exist in the form of sequences of bits (0 and 1) (2013). By definition, they are nonmaterial. Humans can only access them through some physical medium; physical “bearers” like magnetic storage (disk drives), a music device with a digital audio converter (DAC), or when they are ‘printed’ to a physical medium such as speakers, LCD screens or paper (Faulkner and Runde 2019; Yoo and Euchner 2020). Digital objects are created from inputs that come from a human user, sensors, or other machines like a camera or computer; low-level machine-readable instructions transform the input into bitstrings (Kallinikos et al.2013). Once transformed into nonmaterial bitstrings, they can be either stored in another material bearer or can be loaded into the central processing unit to be manipulated by a set of instructions. A basic feature of bitstrings is that to be accessed they must in some way be inscribed onto, contained within, or borne by a material object of some kind (Yoo and Euchner 2020.) The process of writing to and reading from a material bearer has been called “*translational action*” and is the core process in which nonmaterial and the physical are united and embodied.

Faulkner and Runde (2019) call for more rigorous conceptualizations of how these digital and physical artifacts combine. They are concerned with both the simplified grouping vastly heterogeneous technologies (e.g. smart objects, IT infrastructures, software applications, or media files) or equally, the classification of complex combinations and stacks of the material and the nonmaterial as straightforwardly physical things with metaphorical descriptions.

In parallel, other domains of IS research have also called for greater attention to the inflection between the digital and physical (Kyriakou et al. 2017). For example, in the world of conceptual modeling (CM), appeals have been made to reposition the CM discipline toward the world of sensors, ubiquitous computing, and automation, where digital objects express some material agency. They define a new role for CM as the task of mediating the transition from—and between—the states of physical and digital realities (Recker et al. 2021).

Our position is that despite the centrality of translation action as a fundamental activity in inscribing and accessing bitstrings from their material bearers, the activity itself, as well as the technologies that facilitate such translation, are neither adequately conceptualized nor empirically studied within IS research. Our research is an attempt to situate translational action in larger technological stacks of both software and hardware (Schilling 2000; von Briel et al. 2018; Pujol Priego and Wareham forthcoming) to better understand the assemblies, recombination and movements between different components and layers (Henfridsson et al. 2018). Yet, to do so, we need a better understanding of what translational action actually is – if only on a mere technical level – to better theorize the higher-level dynamics.

Ontologies of digital objects

There is an established tradition in information systems and conceptual modeling research that considers ontologies; that is, to study the nature of the world and to organize and describe what reality consists of (Burton-Jones and Weber 2014; Green and Rosemann 2004; Recker et al. 2021). Ontologies are core in IS research because the dominant tradition in information systems design was to accurately assess reality and then codify it in some conceptual modeling syntax from which systems designers build information systems that facilitate greater administrative efficiency for that reality. However, Baskerville et al. (2020) argue that digital technologies increasingly shape reality in what they call an ‘ontological reversal’. With 5G mobile networks, sensors, 3D printing, and virtual reality, digital technology is becoming increasingly immersed in people’s personal and professional lives, actively shaping the physical world in which we live (Baskerville et al, 2020). In many instances, the reality we experience is first created digitally and the physical reality follows as an outcome of this digital facsimile. Moreover, in commercial environments, there is also a temporal reversal in the way that products are manufactured, where a digital representation is created first, and the physical manifestation follows (Baskerville et al. 2020). For information systems, this notion implies a duality: one embodied by the physical world in which we live, and the other embodied by digital codes and signals in networks and computer processing. Yet, at the same time, researchers also allude to some form of digital-physical entanglement (Ekbia 2009; Barrett et al. 2012), superimposition, or fusion of the two: *"*Computed human experience today is one where the digital and the physical are seamlessly and inseparably interwoven" (Baskerville et al. 2020 p 517). Stated differently, "we now see the digital and the physical worlds fused, where digital technology actively shapes the physical world (Baskerville et al. 2020 p 510).*"* Whether the physical and digital are separate, interwoven, or fused, may be a relative assessment. But the relationship is consequential. Accordingly, we turn to our research setting.

Research Context

In this study, we analyze data from the ATTRACT[2] project, a €60M initiative funded by the Horizon 2020 Framework Programme of the European Commission that aims to systematize the discovery of breakthrough applications of imaging, detection, and computational technologies from the leading Scientific Research Infrastructures (SRIs). In Phase 1, ATTRACT supported 170 projects that leverage technologies developed to conduct scientific research toward alternative applications in medicine and life science, energy, security, industry, agriculture, and environmental applications (Romasanta et al., 2021; Wareham et al., 2022). From a submission pool of 1,251 projects, 170[3] projects were awarded seed funding of €100,000 each to develop a proof of concept in 1 year .

We believe that this sample is highly representative of the technologies that support translational action. The technologies developed by SRIs are often unavailable commercially and must be engineered and operated with unprecedented precision to extract data from the physical universe. Perhaps the most famous example is the ATLAS detector at CERN. At 46 m long, 25 m high, and 25 m wide, the 7,000-tonne ATLAS detector is the largest volume particle detector ever constructed consisting of 100 million sensors that measure the masses, momentum, energies, lifetime, charges, and nuclear spins of particles produced in proton-proton collisions. It is an agglomeration of various detection and imaging technologies including calorimetric and pixel detectors, muon spectrometers, semiconductor trackers, and radiation trackers. Another CERN technology that has found uptake in the world of industrial automation is called White Rabbit, a clock and event distribution system for CERN's geographically distributed particle accelerators where time measurement at the nanosecond[4] level is required (Pujol Priego and Wareham, forthcoming). In the field of astronomy, the European Southern Observatory developed a system of deformable mirrors to correct in real-time the distortion caused by the turbulence of the Earth's atmosphere. Lasers are shot up to 90 kilometers into the sky to stimulate sodium molecules that create an artificial star which is monitored as a proxy for atmospheric distortion. One of the telescope's mirrors is extremely thin, less than 2mm, and can be adjusted by 5,000 individual magnetic actuators making 1,000 adjustments per second to correct for atmospheric movement. The European Free Electron Laser recently began operation in Hamburg. It accelerates batches of electrons 3.4 kilometers to a series of 17,000 magnetic undulators that quickly reverse the direction of the electrons. The rapid change of the electrons' direction generates 27,000 hard Xay flashes per second, capable of filming atomic reactions or examining the deep structure and movements of proteins and viruses. Sensing and measurement technologies of this scale, sophistication, and accuracy are often developed for some specific scientific purpose and later migrate to alternative applications in industry (Romasanta et al. 2021.; Pujol Priego and Wareham, forthcoming)

Data and Analysis

We began our open coding of the projects with all 4 authors each reading the project proposals and final delivery reports (when the formal grant was concluded after one year.) Our goal was to understand how the technologies function on the most elemental levels. We met on 3 occasions to discuss the conclusions of the analysis in-plenum and to arrive at a consensus. The first main question was what the mechanism of action for the focal technology was; that is, what was the translational action. For sensors, this typically meant

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[2] https://attract-eu.com/ ATTRACT members include: the European Organization for Nuclear Research (CERN), European Molecular Biology Laboratory (EMBL), European Southern Observatory (ESO), European Synchrotron Radiation Facility (ESRF), European X-Ray Free Electron Laser Facility (European XFEL), and the Institut Laue-Langevin (ILL), Aalto University, ESADE Business School, and the European Industrial Research Management Association (EIRMA).

[3] Full project descriptions can be found here: https://phase1.attract-eu.com/showroom/projects/

[4] A nanosecond (ns) is an SI unit of time equal to one billionth of a second, that is, 1/1,000,000,000 of a second, or 10 – 9 seconds.

identifying how the sensor converted a form of energy (e.g. heat, light, chemical, kinetic) to information (i.e. a bitstring). For actuators, this meant converting bitstrings to kinetic energy (with the addition of a power supply). We also found a category of technologies that remained in the physical domain, such as converting chemical energy to an electric signal, as well as a category that was purely digital (e.g., bitstring manipulation). This produced four main categories highlighted in table 1 below: physical to digital, digital to physical, digital to digital, and physical to physical. Following Faulkner and Runde (2013), we define *digital* as *the generation, manipulation, or interpretation of bitstrings intended for machine or human use*. Where bitstrings will most commonly be sequences of 0s or 1s, other representations are possible. Bitstrings are by definition nonmaterial; anything not in the form of bitstrings is physical. Table 1 details the frequency of the technologies across categories. Note that the total count is 346, due to a technologies' presence in more than one type.

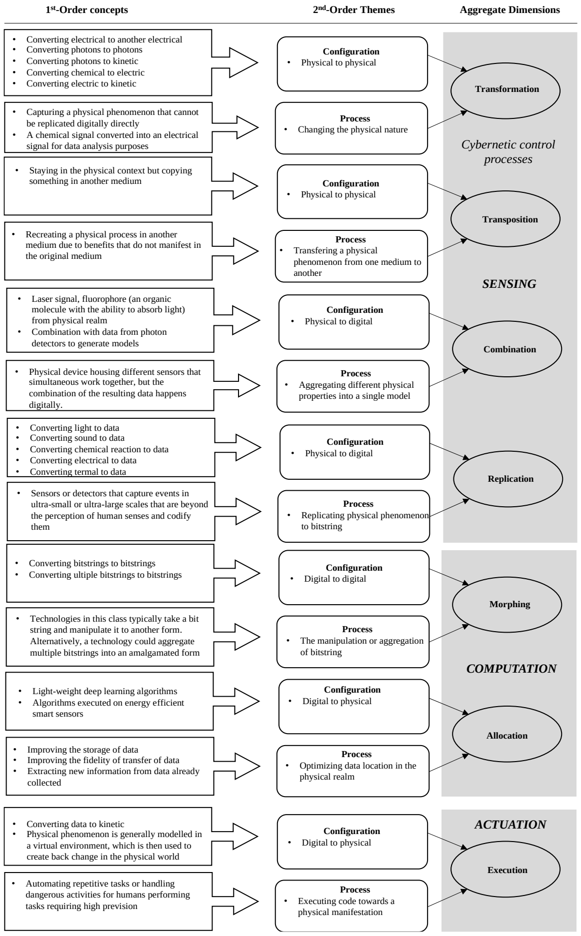
Table 1. Three translational configurations

Translational configurations	Description	Number of occurrences
Physical to digital	photons to bitstrings	98
	electric to bitstrings	51
	chemical to bitstrings	29
	kinetic to bitstrings	11
	thermal to bitstrings	9
	sound to bitstrings	7
	chemical to photons	4
	particles to bitstrings	4
	time to bitstrings	2
Physical to physical	photons to electric	27
	photons to photons	11
	chemical to electric	4
	electric to electric	4
	electric to photons	3
	particles to electric	3
	photons to kinetic	3
	electric to kinetic	2
	electric to thermal	2
	thermal to kinetic	2
Digital to physical	bitstrings to photons	2
	bitstrings to kinetic	3
	bitstrings to electric	2
Digital to digital	bitstrings to bitstrings	29
	Multiple bitstrings to bitstrings	19

Within the open coding stage, our second aim was to focus on the specific attributes of the translational process that digital objects perform when deployed in larger systems; that is, how we could qualify the nature of the translational process. This meant aggregating the empirical descriptions of each type of translational action category into more general groups related to its technical position and function in a larger cybernetic control system or technology stack. We iteratively perform this process, seeking to consolidate redundancies and gradually collapse our codes into first-order categories (Gioia et al. 2013).

In a second analytical step, during axial coding, we gradually sought to progress toward a more abstract and theory-driven explanation. At this stage, we aggregate our first-order categories into seven main processes describing translational processes across the four types of translational configurations: replication, combination, allocation, execution, transformation, transposition, and morphing. We performed this step in several iterations, where all 4 authors engaged in the analysis making extensive use of notes and personal observations to interpret the data. Figure 1 presents the final data structure resulting from this phase.

Figure 1. Data Structure



Preliminary Findings

Our analysis of the 170 technologies revealed four distinct translational configurations through which technologies enabling translational action function in larger systems. Across these three configurations, our analysis uncovers seven distinct translational processes. We describe them in turn and empirically illustrate them with descriptive references to the analyzed projects.

Four translational configurations

Physical to digital. As an illustration of the physical to digital configuration, in medical diagnostics, lasers can be used to analyze gene expression liquid biopsies for common cancers. The laser signal can excite fluorophore (an organic molecule with the ability to absorb light at a particular wavelength and then emit it at a higher wavelength) in a molecular beacon that binds to the mutated gene. When combined with highly sensitive single-photon detectors, data are generated to inform disease progression, therapy selection and patient prognosis. This translational action is *photons to bitstrings*.

Digital to physical. The IoT requires ultra-low-power non-volatile memories to enable IoT devices to be autonomous. Such memories work at very low voltages and are capable of robustly storing data almost indefinitely, only consuming power when triggered by some event that produces an electrical signal with the bit-string. This translational action is between *bitstrings and electrical energy*.

Physical to physical. An example of the physical-to-physical configuration comes from the use of biological elements as sensors. Bacteria can be genetically modified to bioluminesce in the presence of specific chemicals. For example, bacteria can luminate in the presence of 2,4- dinitrotoluene (DNT), an indicator of the presence of buried landmines. In our classification, this would be the translational action between *chemical energy and photons*. In the category of actuators, an interesting example is the use of laser technology at a nanometre scale (1-100 nm) to conduct laser-based manufacturing on a scale smaller than the wavelength of light. The ability to manipulate molecules at the nanometre scale (1-100 nm) is critical for the manufacture of practical nano-technology devices. The use of laser light (photons) to manipulate matter is a translational action from *photons to kinetic energy*.

Digital to digital. Technologies in this class typically take a bit string and manipulate it to another form. Alternatively, a technology could aggregate multiple bitstrings into an amalgamated form.

Within these four configurations, we identify different translational processes across the 170 projects analyzed, which we describe in turn. Note that the total count is 220, due to a technologies' presence in more than one type.

Seven translational processes

Table 2. Seven types of translational actions

	Translational process	Description	Count
1	Replication	*Replication* is performed to observe a physical phenomenon not possible to observe before. This action is contingent on the use of new sensors or detectors that measure phenomena in ultra-small or ultra-large scales that are beyond the perception of human senses. The phenomenon is then replicated in a digital representation/bitstring. Through this digital representation, the physical phenomenon can be studied deeply and eventually modified in ways that were not possible previously in the physical realm.	131
2	Combination	*Combination* consists in bringing together multiple information signals from the physical to the digital realm for modelling purposes. This can include having different sensors and then combining the generated data in the digital realm or combining the different readings before the translational action is conducted. Combination in the digital realm is especially valuable when combined in the physical world is complex or impractical. For instance, a physical device can house different sensors that simultaneously work together, separately sensing and thereafter combining the resulting data.	30
3	Execution	*Execution* involves converting bitstrings to physical actions. Manifesting code to the physical realm is useful for many applications such as automating repetitive tasks, handling dangerous activities for humans, or doing something requiring high precision. In complex cases, a physical phenomenon is generally modelled in a virtual environment and is subsequently actuated in the physical world. For instance, in surgery, digital models can be combined with surgeon actions that are further actuated through robotic arms and instruments towards greater precision.	28
4	Allocation	*Allocation* refers to the optimization of storage or transfer of data in the physical realm. Here, data remain in their digital form, but its physical manifestation is modified for performance improvements. In making the storage and distribution of data more efficient, it is easier to manipulate data for highly complex operations. Similarly, ensuring that data is transferred with high fidelity across different physical devices is an enabler for different technology applications.	14
5	Transformation	*Transformation* involves changing the physical nature of an object. From converting fuel to mechanical energy in cars to converting food to energy in organisms, transformation is one of the more prominent translational actions across our sample. Transformation appears usually as a technical requirement to be able to capture a physical phenomenon that cannot be replicated digitally directly. For instance, a chemical signal might have to be converted into an electrical signal to further enable data analysis.	13
6	Transposition	*Transposition* consists of taking a natural physical process and transforming it to a similar one into another physical media or substrate. Recreating a process or object in another form is to realize qualities that do not manifest in the original medium. However, transposition across physical forms can be more difficult compared to replication in the digital realm.	6
7	Morphing	*Morphing* is the process in which bitstrings are manipulated or combined in computational processes, data restructuring and manipulation, or distribution and storage.	4

Discussion

By dissecting translational actions across physical and digital layers, our study offers an opportunity to reflect on the ontology of hybrid technology objects that simultaneously operate at the physical and digital. Consider a self-driving car: is it a single ontological entity; or is it a complex combination of thousands of interdependent components that sense and respond to its operational environment? For the marketer, anthropologist, or customer, it is likely one unified entity. For the engineer that designs it, the sourcing manager that buys the components, or the regulator that needs to identify its most critical points of failure, it is more useful to consider it as a complex aggregation of coupled elements. In a world with increasing deployment of sensors, edge computing, and automation, better insight into translational action is useful to understand the interaction, process, and resources consumed at each stage, particularly high for public safety risks domains such as transportation, manufacturing, or energy where automation is prevalent.

Wiener (1948) defined cybernetics as the science of control and communications in the animal and the machine. Cybernetic control requires sampling the value of some parameter of interest, comparing it with a desired value or range, and adjusting the system's behavior accordingly through the controller (Åström and Murray 2008). This basic feedback loop of *sensing*, *computation* and *actuation* is the central concept in control theory and automation. To better understand automation, we describe how our categories of translational action map to cybernetic control processes. While cybernetic controls are typically closed-loop (circular) systems, there is an implied process that is represented in the ordering of the translational action below (translational actions 1-7).

(1&2) Before the sensor can register a signal, the signal may need to be *transformed* to another physical form or *transposed* to a different sensing substrate. (3&4) Multiple physical signals may need to be *combined* before they are *replicated* in a bitstring. (5) Once converted into a bitstring, the manipulation or aggregation (*morphing*) of bitstrings may be required for computation and analysis. (6) From here, sensory data can be *allocated* in either single or distributed historical data storage for subsequent comparison and analysis. (7) Bitstrings are then *actuated* into physical action with the addition of a power source and some mechanism.

Table 3. Cybernetic control and translational action

Cybernetic control Process	**Translational configuration**	**Translational action**	**Description**
Sensing	Physical-physical	1. Transformation 2. Transposition	If the signal is not in the correct form for sensing, some modification of the signal or transposition to a different media may be needed.
	Physical-digital	3. Combination 4. Replication	Either the physical signal is directly converted to a bitstring, or prior to replication, multiple physical signals are aggregated into a composite signal.
Computation	Digital-digital	5. Morphing	The manipulation or aggregation of bitstring may be needed in morphing.
	Digital-physical	6. Allocation	Sensory data are stored for analysis in single or distributed repositories.
Actuation		7. Execution	Bitstrings are combined with a power supply to actuate some physical action (e.g., in a SCADA system.)

The implicit ordering of translation actions through cybernetic control cycles requires additional empirical validation. Additionally, our study seeds the ground for future research that contributes to answering questions such about the nature of their combinations and interactions, such as: Are there forms of translational action that are more or less compatible, scalable, or robust across physical-digital, digital-physical, digital-digital, and physical-physical modalities? Do instances of translational action exhibit systemic properties when combined in larger, heterogeneous combinations? How can a deeper understanding of translational action inform the study of ontologies or related disciplines of conceptual modelling for hybrid technology objects? And what can these insights tell us about the nexus of the physical and digital in large, complex, automated systems?

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