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Adaptation of ISO 23247 to Aerospace Digital Twin Applications: On-Orbit Collision Avoidance and Space-Based Debris Detection

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As interest in digital engineering within a variety of technical domains begins to accelerate, industries continue to encounter obstacles with regard to implementing—and benefiting from—digital twin technologies. One key challenge facing digital twin adoption in the aerospace industry, in particular, is a lack of standardized digital twin frameworks (DTFs). Adapting existing DTF standards intended for use in other domains towards aerospace applications may offer a path forward for overcoming this obstacle. To demonstrate the feasibility of this approach, the recently published ISO 23247 standard, Digital Twin Framework for Manufacturing, is adapted for the first time for use in a non-manufacturing aerospace application—collision avoidance (COLA) in low Earth orbit (LEO) for resident space objects (RSOs) greater than 10 cm in characteristic length. The result is the first known formal representation in a standardized digital twin framework of this well-established prescriptive COLA process. To further demonstrate the value of establishing a standard aerospace DTF, this framework is, in turn, adapted into a novel descriptive digital twin architecture for space-based detection of sub-10-cm-class orbital debris, which can later be integrated with the existing collision avoidance framework to improve overall space situational awareness (SSA). The paper concludes with recommendations for future work on the development of increasingly sophisticated digital twins of the LEO space environment, leveraging these frameworks as a baseline.

I. Introduction

The term “digital twin” refers to an emergent technology that seeks to represent a physical system or environment in a virtual form. Moreover, digital twin frameworks (DTFs) expand upon this concept by integrating the virtual systems or environments and their physical counterparts to capture the relevant cyber-physical elements and their interrelationships in a formal, multi-layer system definition. In particular, in an earlier work, Shao et al. define the five categories of digital twins, in order of increasing complexity and value [1]:

1) **Descriptive digital twins**, which seek to represent or *describe* the system or environment using available data from observations;
2) **Diagnostic digital twins**, which seek to explain *why* the system or environment is in its current state;
3) **Predictive digital twins**, which seek to *predict* the future state of the system or environment using analytic and propagative tools;
4) **Prescriptive digital twins**, which seek to optimally *realize* (or *avert*) the prediction by commanding entities within the physical system, often with human-in-the-loop intervention; and
5) **Intelligent digital twins**, which seek to minimize or eliminate human-in-the-loop intervention with additional layers of *autonomy* and *artificial intelligence*.

Although the modern definition of digital twins only received widespread recognition in the early 2000s, several industries have benefited from digital twins in various forms for decades [2]. The aerospace industry, in particular, has a rich history involving digital twin technologies and philosophies, dating at least as far back as the National Aeronautics and Space Administration’s (NASA’s) historic rescue of Apollo 13 in April of 1970 [2]. More recently, the U.S. Department of Defense (DoD) has awarded a number of contracts encouraging the development of digital engineering tools to support satellite constellation design, active space debris monitoring and remediation efforts, and other space operations, which indicates the U.S. government’s continued interest in promoting and leveraging digital

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twin technologies in this domain [3, 4]. In spite of these facts, the American Institute of Aeronautics and Astronautics (AIAA) Digital Engineering Integration Committee recently published a unified implementation paper identifying a number of challenges—including lack of standardization—that are preventing the widespread adoption of digital twins in aerospace and identified a need for general, standardized digital twin reference models that can be adapted for particular aerospace applications [5].

One approach towards the development of standardized digital twin frameworks for aerospace applications involves the adaptation of existing, published digital twin standards intended for applications within other domains. For example, Ref. [5] offers a case study in which the recently published ISO 23247 standard [6] for digital twins in manufacturing is successfully applied to three distinct aerospace manufacturing test cases. A close inspection of this standard suggests that the ISO 23247 digital twin architecture can be readily adapted into other domains, such as non-manufacturing aerospace. To demonstrate this flexibility, this paper presents a case study that adapts the ISO 23247 framework to a topical aerospace application—on-orbit collision avoidance.

The recent proliferation of satellites in low Earth orbit (LEO) as part of the burgeoning space economy poses a number of challenges in the form of space debris mitigation and collision avoidance (COLA) [7]. As the number of resident space objects (RSOs) in LEO grows, the risk of collision between RSOs increases dramatically, threatening the sustainability of Earth's local space environment [7]. Frequent monitoring and cataloging of RSOs is necessary to prevent the disruption of space-based communication networks, global navigation systems, and other critical services that benefit hundreds of millions of U.S. residents on a daily basis. The U.S. Space Surveillance Network (SSN) currently tracks over 23,000 RSOs in LEO, including functional and decommissioned satellites and debris, focusing on objects with characteristic length greater than 10 cm due to ground-based sensing limitations [8].

The process for detecting conjunctions—or close approaches—and avoiding collisions between these larger RSOs is facilitated by a *de facto* prescriptive digital twin of the (partial) LEO space environment. In particular, the SSN updates a High-Accuracy Catalog (HAC) of position and velocity estimates at least once per day using ground-based sensor measurements [9]. The 18th Space Defense Squadron (18 SDS) then propagates these estimates several days into the future and updates the HAC accordingly, while the 19th Space Defense Squadron (19 SDS) screens the HAC to assess collision risk for each RSO. If an active spacecraft (S/C) is at sufficiently high risk of collision, the 19 SDS uses a web-based application known as Space-Track to send a conjunction data message (CDM) or collision avoidance notification (CAN) to the satellite's owner/operator (O/O) (e.g., NASA), which may (or may not) manually or automatically correct the satellite's trajectory based on available information to mitigate the risk [9]. The SSN then obtains a new set of measurements using its suite of sensors, and the cycle repeats. Fig. 1 below depicts this overall process at a high level. Section III discusses the various operations depicted in Fig. 1, as well as additional activities and functionalities, in greater detail.

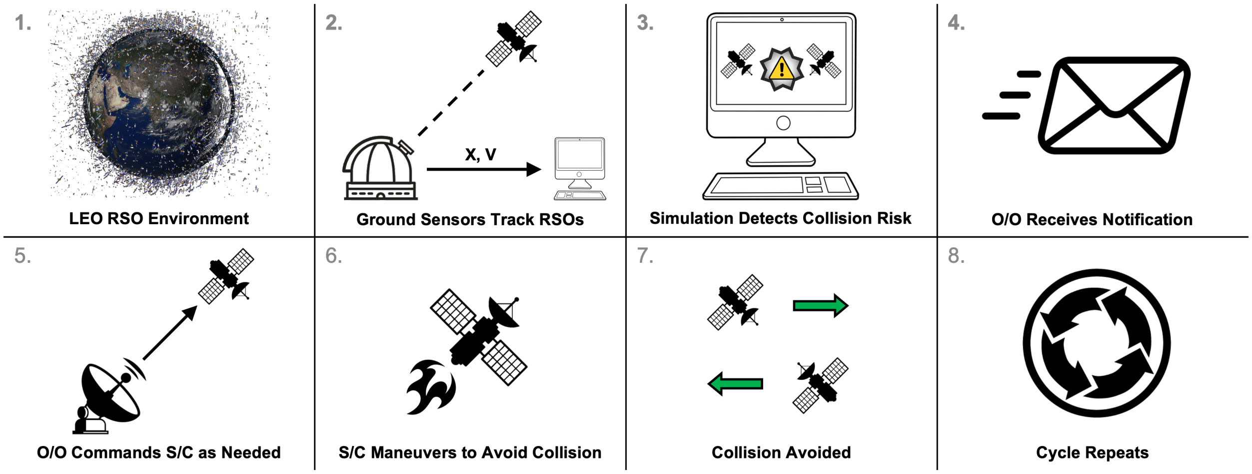

Fig. 1 Concept of operations for collision avoidance using ground-based sensor measurements of LEO RSOs. Image in Box 1 courtesy of European Space Agency (ESA) via *National Geographic* [10].

The above process has been depicted in a number of forms throughout the years [9, 11, 12] but has rarely, if ever, been depicted as a digital twin in a formal sense. In light of this fact, this paper applies and adapts the recently developed

ISO 23247 standard [6] to capture the process in a standardized prescriptive digital twin framework. Although the ISO 23247 standard is defined for digital twins in manufacturing, the components defined in the standard User, core Digital Twin, Data Collection and Device Control, and Cross-System Entities, as well as the observable elements, are broadly applicable to human-in-the-loop satellite operations. Consequently, with some level of tailoring of these components, a prescriptive digital twin architecture for detection and avoidance of LEO RSOs greater than 10 cm in characteristic length can likewise be developed, as is discussed in Section III. This ultimately offers an intermediary step towards meeting the AIAA Digital Engineering Integration Committee's call to improve standardization for digital twins in aerospace [5].

In particular, the formal representation of an *existing* space situational awareness (SSA) system within a digital twin framework encourages investigation into the establishment of novel DTFs for similar aerospace processes that are forthcoming or in development. For instance, at the time of this writing, no such formal DTF exists for *space-based* detection of debris and other RSOs using sensors external to the SSN, in spite of recent publications exploring the feasibility and value of such an approach [11, 13–19]. As an example, recent work by Shtofenmakher and Balakrishnan indicates that commercial optical sensors available onboard most active satellites can, under appropriate lighting conditions, be used to detect sub-10-cm-class debris in LEO [17, 18]. These space-based measurements could be transmitted to the ground through radio frequency or optical communication methods and received by a corresponding ground station [20]. These data can be processed by ground software and ingested into a database accessible by the SSN and other interested stakeholders. End users can then visualize the LEO space debris environment with appropriate front-end simulation software.

The above paragraph describes, at a high level, a *descriptive* process for orbital debris detection by on-orbit satellites using in-space sensors, which can likewise be captured in a novel digital twin framework. Section IV explores this DTF, including its constituent elements and their interrelationships, in greater detail. In contrast to the architecture presented in Section III—which captures an existing process that primarily leverages ground-based sensors within the SSN to track larger RSOs—the framework presented in Section IV offers a baseline for the development of digital twins designed to virtually represent smaller RSOs in the LEO environment using data collected from space-based sensors. Although any descriptive digital twin derived from this DTF could operate independently from the existing prescriptive process for collision avoidance, in the ideal case, the two digital twins would cooperate to provide improved SSA and COLA capabilities. With additional development, an initially descriptive digital twin for space-based orbital debris detection can evolve to have diagnostic, predictive, prescriptive, and even intelligent capabilities for collision avoidance within satellite networks. This is presented as future work in Section V.

In summary, this paper claims the following contributions to the digital engineering literature:

1) The first known adaptation of the ISO 23247 standard [6] to a non-manufacturing aerospace application;
2) The first known formal representation in a standardized digital twin framework of the existing prescriptive process for detecting and avoiding collisions between RSOs in LEO; and
3) A novel descriptive digital twin framework for sub-10-cm-class orbital debris detection by on-orbit satellites, to be used in augmenting the existing collision avoidance process—which does not typically account for debris particles of this size class—and as a baseline for the development of a series of increasingly sophisticated digital twins for space-based debris detection and collision avoidance within satellite networks.

II. ISO 23247 Standard Architecture for Digital Twins in Manufacturing

The recently published ISO 23247 standard, Digital Twin Framework for Manufacturing, offers a generic digital twin reference architecture intended to be adapted for specific applications within the manufacturing domain [21]. Although the standard contains four parts at the time of this writing, the present discussion will focus on Part 2: Reference Architecture [6].

Figure 2 depicts the ISO 23247 standard architecture for digital twins in manufacturing [6].

In this framework, the physical entities intended to be represented by their virtual counterparts are collectively termed **Observable Manufacturing Elements** (OMEs). An OME is defined in ISO 23247 as "an entity that has an observable physical presence or operation in manufacturing" [6]. In Fig. 2, these are captured within the gray box at the bottom of the figure. The remaining entities are enclosed within an overall **Digital Twin Framework**, represented by the dashed box.

The DTF is resolved into four **major entities** (depicted in Fig. 2 as darker blue boxes), each of which is defined primarily by its main function or functions, which are represented by **functional entities** (FEs, depicted as white boxes).

The **User Entity** (UE), which includes humans directly involved in the operation and management of the digital

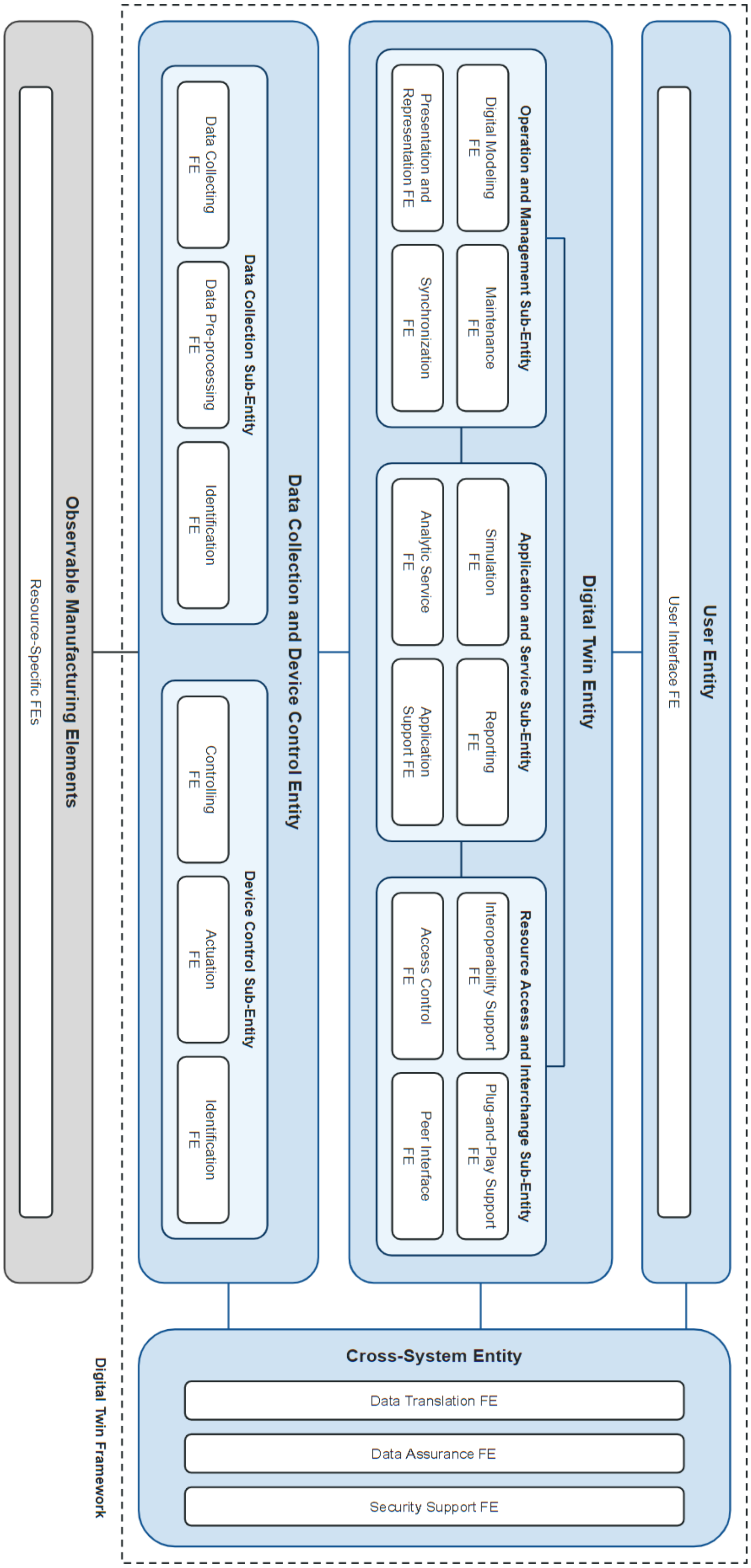

Fig. 2 The ISO 23247 standard architecture for digital twins in manufacturing [6], modified in appearance from the original to increase accessibility.

twin, provides user interfaces to interact with the core digital twin entity [21].

The **Digital Twin Entity** (DTE), also known as the **Core Entity** (CE), serves to digitally represent and manage the observable physical elements (i.e., OMEs) with a number of **sub-entities** (depicted in 2 as lighter blue boxes), each of which is likewise defined by its major functions [21]:

1) The **Operation and Management Sub-Entity**, which manages the digital model and its maintenance, synchronization, and visualization;
2) The **Application and Service Sub-Entity**, which manages simulations, data analysis, and report generation; and
3) The **Resource Access and Interchange Sub-Entity**, which manages interoperability among and access to the digital twin elements.

The **Data Collection and Device Control Entity** (DCDCE) links the observable physical elements to their virtual counterparts via two sub-entities [21]:

1) The **Data Collection Sub-Entity**, which collects data from the observable physical elements using sensors and communicates those data to the DTE via networks; and
2) The **Device Control Sub-Entity**, which controls and actuates the observable physical elements based on inputs from the UE, the DTE, or both, depending on the specific application.

The **Cross-System Entity** (CSE) resides across domains, typically interacting with the other entities at multiple levels with functions like data translation and assurance and cybersecurity [21].

The major entities, including the observable physical elements, and the sub-entities within them are connected to one another via a series of defined networks [21]:

1) The **user network**, which connects the UE and the DTE;
2) The **service network**, which connects the various sub-entities within the DTE;
3) The **access network**, which connects the DCDCE to the DTE and the UE; and
4) The **proximity network**, which connects the DCDCE to the observable physical elements.

In Fig. 2, the color of each network connection matches the color of the frame of one or both of the boxes to which it connects. It is worth noting that the original ISO 23247 standard architecture in Ref. [6] allows for—but does not explicitly depict—the access network connection between the UE and the DTE [21]. For maximum fidelity to the source material, the replication presented in Fig. 2 likewise omits this connection.

Although ISO 23247 is defined for digital twins in manufacturing, the reference architecture is ultimately presented at a relatively high level, with lower-level details regarding individual FEs and networks omitted in favor of increased generality. The result is an adaptable framework that, with some effort, can be tailored to applications both within manufacturing (e.g., drilling and filling holes in airframe wings [5]) and beyond (e.g., collision avoidance in LEO). With regards to the latter, the challenge arises in translating each of the entities and elements from the ISO 23247 architecture into their counterparts in a particular aerospace application, as well as identifying superfluous elements that can be eliminated and supplemental elements that need to be added for a more complete digital representation. This adaptable nature and its corresponding challenges are explored in Section III and Section IV.

III. Prescriptive Digital Twin Architecture for On-Orbit Collision Avoidance

As discussed in Section I, the current process for detecting conjunctions and avoiding collisions between RSOs tracked by the U.S. SSN can be captured within a prescriptive digital twin framework, in which the core digital twin seeks to represent, at least in part, the LEO RSO environment. To harness this potential, this section adapts the ISO 23247 digital twin reference architecture towards this aerospace application, presenting both higher-level and lower-level functional representations and offering associated discussions [6]. Much like the ISO 23247 standard, this section begins by defining terminologies that will be used in the remainder of the text, then presents a high-level digital twin reference architecture for on-orbit collision avoidance, and ends with lower-level details regarding the individual elements within that architecture and their corresponding interrelationships [6].

A. Relevant Terminology

Several key terms briefly mentioned in Section I are formally defined here:

1) **Space situational awareness**, or SSA, refers to "the ability to accurately characterize the space environment and activities in space" and generally involves acquiring knowledge regarding the current and future positions of space objects of interest [19].
2) **Conjunction data messages**, or CDMs, are messages sent to spacecraft O/Os by the 19 SDS informing them of upcoming conjunctions over the next few days [9].

3) **Collision avoidance notifications**, or CANs, are notifications sent to spacecraft O/Os by the 19 SDS indicating that one of their space assets has met emergency close approach conditions, with probability of collision roughly 1000 times greater than that required to issue a CDM [9].

The 18 SDS and 19 SDS also offer the following definitions in their *Spaceflight Safety Handbook for Satellite Operators* [9]:

1) The **state** of an RSO, in the context of this framework, refers to the concatenated position and velocity vectors of that RSO at a given moment in time.
2) An **ephemeris** (plural: **ephemerides**) for an RSO refers to a series of state (i.e., position and velocity) vectors for that RSO presented sequentially in time.

For brevity, the description of the collision avoidance process presented in Section I focused on position and velocity estimates generated by the U.S. SSN. However, certain O/Os may choose to contribute to the 18 SDS & 19 SDS RSO databases by willingly sharing the SSA information available to them [9]. The following definitions serve to distinguish O/O and S/C types based on their respective levels of cooperation and collaboration, wherein the former is generally considered a prerequisite for the latter:

1) These **Collaborative O/Os** may provide onboard-sensor-based position and velocity data and predictive ephemeris data for their own S/C and will consider maneuvering their spacecraft and providing associated maneuver notifications in response to a relevant CDM.
2) Accordingly, **Collaborative S/C** are those S/C under the purview of Collaborative O/Os.
3) Strictly **Cooperative O/Os**, on the other hand, will consider maneuvering their spacecraft in response to a CDM but will generally not provide maneuver notifications or share SSA information concerning their own spacecraft willingly.
4) Since cooperation is generally a prerequisite for collaboration, **Cooperative S/C** are those that can be maneuvered by Collaborative O/Os or strictly Cooperative O/Os.
5) **Uncooperative O/Os**, in contrast, will not consider maneuvering their spacecraft in response to a CDM and will not generally share SSA information willingly. This may include O/Os of inactive or otherwise non-maneuverable spacecraft as well as adversarial nation-states with S/C involved in CDMs [8].
6) **Uncooperative S/C** are, therefore, those that cannot be maneuvered by Collaborative O/Os or strictly Cooperative O/Os.

These O/O and S/C categorizations are loosely derived from similar terminology in Ref. [8], intended for cooperative spacecraft maneuvering applications, wherein the second actor in a(n):

1) *Collaborative* COLA situation actively shares information and is willing to maneuver;
2) *Cooperative* COLA situation is willing to maneuver but does not necessarily coordinate with the first actor; and
3) *Uncooperative* COLA situation neither shares information nor maneuvers.

With the necessary key terms defined, the following sub-section will present a high-level functional representation of the on-orbit collision avoidance digital twin reference architecture.

B. High-Level Digital Twin Architecture

Figure 3 seeks to capture the existing process for on-orbit collision avoidance in the form of a high-level prescriptive digital twin architecture. The emphasis in this figure is on the major entities, their sub-entities, and the information exchanged among them through the various digital twin networks. Additional details regarding the individual functional entities captured within the major entities and sub-entities are provided in the next subsection.

The color scheme in Fig. 3 is similar to that of Fig. 2, with two key differences:

1) Lighter gray boxes representing observable physical *sub-entities* are now embedded within the darker gray box representing observable physical entities; and
2) The color of each network connection matches the color of the frame of the box from which it is *sourced*.

Although the emergent behavior of this particular application is on-orbit collision avoidance, this digital twin ultimately seeks to represent, in virtual form, the LEO RSO environment encapsulating the observable physical elements. These **Observable LEO Resident Space Objects** are resolved into two categories: Uncontrollable and Controllable. The set of **Uncontrollable LEO Resident Space Objects** includes uncooperative spacecraft and debris of characteristic length greater than 10 cm, whereas the set of **Controllable LEO Resident Space Objects** includes both cooperative and collaborative spacecraft. In this application, debris of characteristic length *smaller* than 10 cm is not considered observable and is therefore not included.

Each of these Observable LEO RSOs, Controllable or Uncontrollable, is tracked by ground-based radar and optical

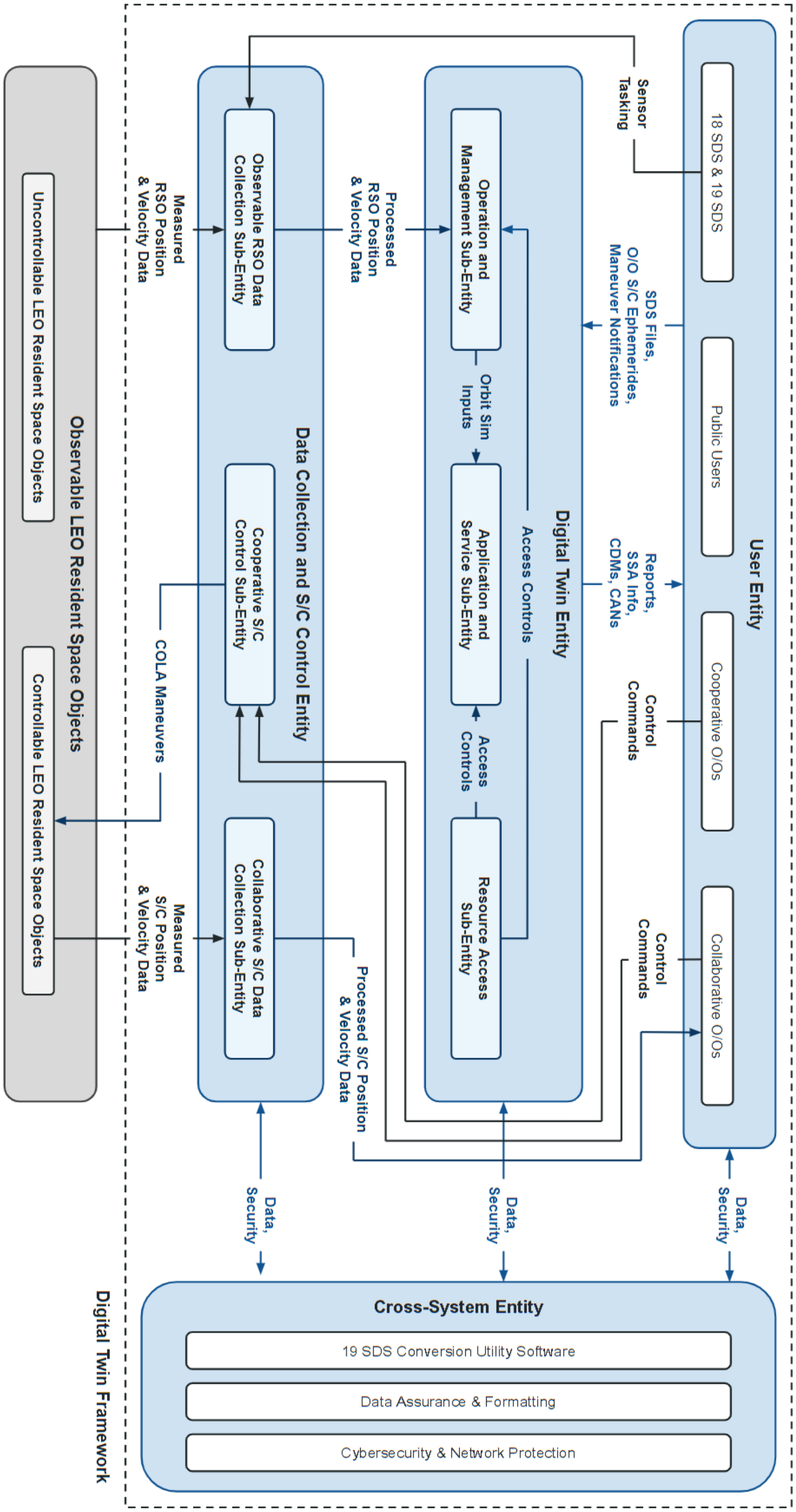

Fig. 3 A higher-level prescriptive digital twin architecture for on-orbit collision avoidance, with a focus on the information exchanged among major entities, sub-entities, and functional entities.

sensors—as well as a few space-based sensors, such as those on the Space-Based Surveillance System (SBSS)—within the U.S. SSN based on sensor tasking commands received by 18 SDS and partnered SSN sensor operators [9, 19]. The collection of these data is represented in Fig. 3 as measured RSO position and velocity data being received by the **Observable RSO Data Collection Sub-Entity** within the **Data Collection and *Spacecraft* Control Entity**, an application-specific variant of the DCDCE from ISO 23247. Once these data are processed, they are passed into the **Digital Twin Entity's Operation and Management Sub-Entity**, which synchronizes the data, determines the orbit of each observable LEO RSO, and outputs orbital simulation parameters [9]. These are ingested by the **Application and Service Sub-Entity**, which simulates and propagates the RSO orbits, analyzes the data, and detects conjunctions [9]. The **Resource Access Sub-Entity** manages access controls throughout the DTE, which ultimately makes reports, CDMs, and additional SSA information available to users via the Space-Track application [9].

Within the **User Entity**, users of Space-Track—and, by extension, the overall digital twin of the LEO RSO environment—include **18 SDS & 19 SDS**, **Public Users** such as Dr. T.S. Kelso and his publicly available Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES) tool [22], **Cooperative O/Os**, and **Collaborative O/Os**. 18 SDS & 19 SDS may upload various files to Space-Track, while Collaborative O/Os may upload their spacecraft ephemerides and maneuver notifications [9]. Collaborative O/Os determine spacecraft ephemerides based on processed spacecraft position and velocity data received from their own spacecraft via the **Collaborative S/C Data Collection Sub-Entity**, which collects, stores, and processes spacecraft data.

In the event of a CDM or CAN, both Collaborative O/Os and strictly Cooperative O/Os may send control commands to the **Cooperative S/C Control Sub-Entity**, which controls individual Controllable LEO RSOs through collision avoidance maneuvers executed via spacecraft actuators such as thrusters.

Throughout this process, the **Cross-System Entity** ensures that any data received by an FE are properly formatted, trustworthy, and secure.

C. Mapping of Functional Entities

Figure 4 expands on the higher-level architecture depicted in Fig. 3 by providing additional detail regarding the embedded functional entities. The color scheme in Fig. 4 is similar to that of Fig. 2, with the addition of the lighter gray boxes representing observable physical sub-entities within the darker gray box representing observable physical entities.

This section seeks to offer an approximate mapping of the ISO 23247 functional elements depicted in Fig. 2 to those identified in Fig. 4. Given the differences between the two applications—manufacturing vs. collision avoidance in LEO—the overall mapping is not one to one; however, many FEs translate from one application to the other in an exact or approximate manner.

For example, the **Resource-Specific FEs** categorized under Observable Manufacturing Elements in Fig. 2 map to a different set of observable entities: **Large Debris (> 10 cm)** and **Uncooperative O/O Spacecraft** within the Uncontrollable LEO RSOs Sub-Entity and **Cooperative O/O Spacecraft** and **Collaborative O/O Spacecraft** within the Controllable LEO RSOs Sub-Entity. These differences arise naturally from the difference in application, but the observable nature of the elements is shared.

Similarly, the DCDCE from the ISO 23247 standard is re-envisioned in Fig. 4 as a Data Collection and Spacecraft Control Entity with three sub-entities, rather than two, due to application-specific nuances. In particular, the Observable RSO Data Collection Sub-Entity receives commands from the 18 SDS & 19 SDS FE, collects data on both Controllable and Uncontrollable LEO RSOs, and outputs processed data to the DTE. In contrast, the Collaborative S/C Data Collection Sub-Entity receives data only from Collaborative O/O Spacecraft and outputs this information directly to Collaborative O/Os, which can then upload O/O S/C ephemerides to the DTE via Space-Track [9]. Combining these two data collection sub-entities into a single Data Collection Sub-Entity, as in Fig. 2, would simplify the prescriptive digital twin architecture for on-orbit collision avoidance at the expense of valuable nuance. Thus, Fig. 3 and Fig. 4 separate data collection on the part of the SSN from spacecraft control and data collection on the part of O/Os for additional clarity.

In each case, the mapping of FEs is straightforward. For the Observable RSO Data Collection Sub-Entity, the **Data Collecting FE** is resolved into the suite of sensors and related hardware—that is, the **U.S. Space Surveillance Network**—used to collect SSA data for the HAC and a **Data Collection and Storage** FE. The **Data Pre-processing FE** from ISO 23247 corresponds directly to the **Data Processing** element in Fig. 4. This FE reflects the process by which sensor readings are weighted and filtered to increase the accuracy of the information received over multiple points in time, using methods like weighted least squares regression, based on parameters that contribute to measurement uncertainty, like weather conditions, time tracked, geometric constraints, power constraints, and technical difficulties

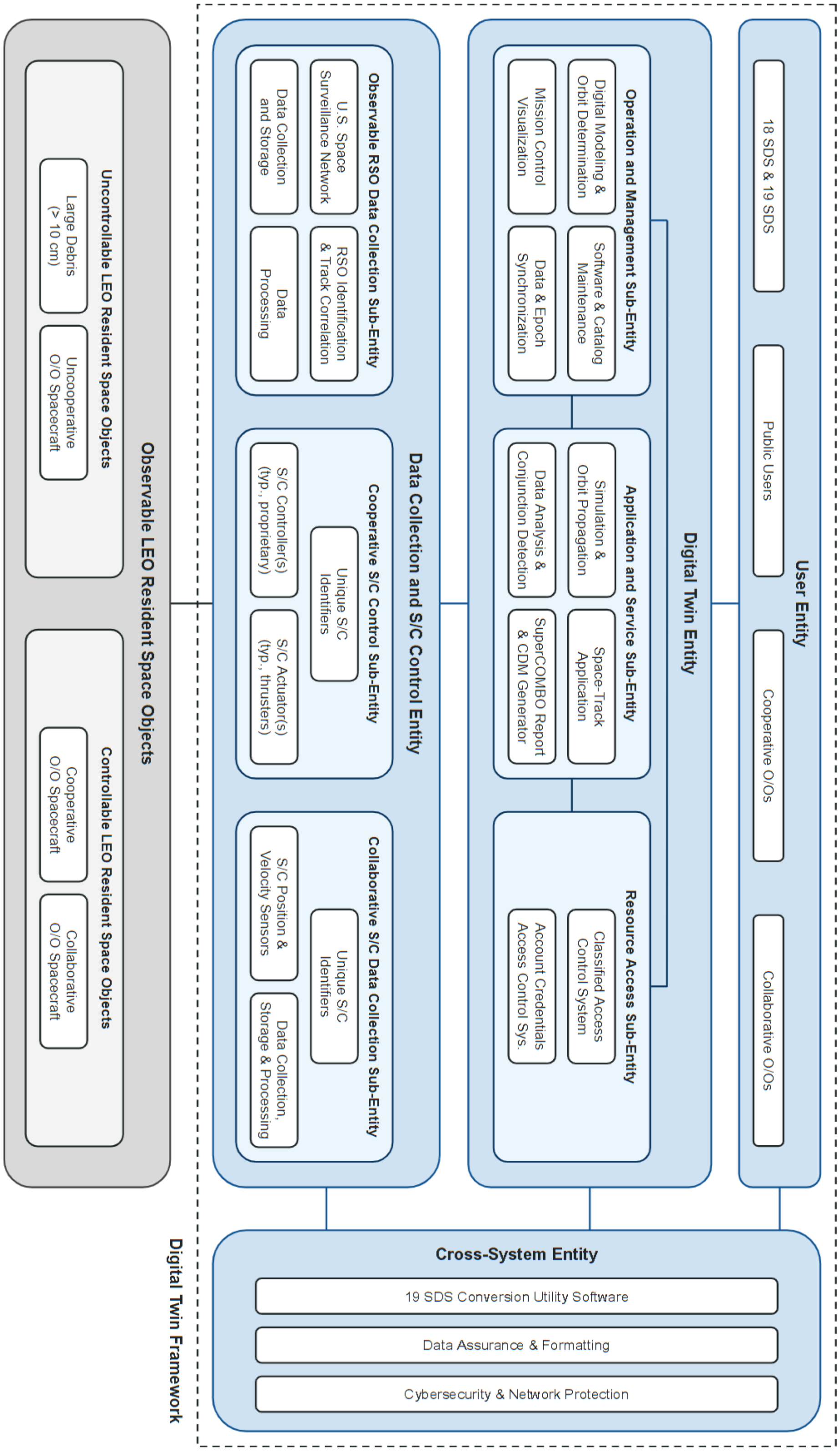

Fig. 4 **A lower-level prescriptive digital twin architecture for on-orbit collision avoidance, with a focus on enumerating the functional elements constituting the entities and sub-entities.**

[23, 24]. The **Identification FE** maps to the **RSO Identification & Track Correlation** system used by the SSN and the 18 SDS. In particular, the sensor tasking commands received by the SSN typically include a set of known RSOs and their expected locations [24, 25]. For each such already identified RSO, the SSN scans the corresponding region of space and correlates the associated tracking data to estimates generated from catalog propagation [26]. For tracks that do not correlate to any known space objects—e.g., uncatalogued RSOs—a state estimate is generated and assigned to the object [23]. After several (typically, three or four) consistent track associations, the RSO is assigned a unique identifier and added to the catalog [23, 26].

Likewise, for the Collaborative S/C Data Collection Sub-Entity, **S/C Position & Velocity Sensors** take the place of the **Data Collecting FE**. **Unique S/C Identifiers**, which O/Os use to uniquely identify their spacecraft and to correlate received position and velocity readings with their corresponding vehicles, replace the generic **Identification FE** from Fig. 2 [27]. For example, the Consultative Committee for Space Data Systems (CCSDS) 320.0-M-7 standard, “CCSDS Spacecraft Identification Field Code Assignment Control Procedures,” offers recommended practices for such unique spacecraft identifiers [27]. Onboard spacecraft **Data Collection, Storage, and Processing** is derived from the **Data Collecting FE** and the **Data Pre-processing FE** from the ISO standard.

The FEs of the Cooperative S/C Control Sub-Entity in Fig. 4 map nearly directly to those of the Device Control Sub-Entity in Fig. 2. As before, **Unique S/C Identifiers**, which O/Os also use to ensure that commands are being sent to the correct vehicle, replace the generic **Identification FE** from the ISO 23247 standard [27]. CCSDS 320.0-M-7 once again provides recommended practices on this topic [27]. Likewise, the generic **Controlling FE** is replaced by **S/C Controller(s)**, which is (are) often proprietary control algorithms used to convert O/O commands into actuator operations [20], and **Actuation FE** is replaced by **S/C Actuator(s)**, which, for the purposes of collision avoidance maneuvers, are typically thrusters [24].

Within the DTE, the roles of the three sub-entities are largely similar between the ISO 23247 standard and the formalized prescriptive framework, with the individual FEs tailored for the on-orbit collision avoidance application.

Within the Operation and Management Sub-Entity, the **Digital Modeling & Orbit Determination** FE, derived from the **Digital Modeling FE** of ISO 23247, ingests processed position and velocity data from the Observable RSO Data Collection Sub-Entity and O/O S/C ephemerides from the User Entity (via Space-Track) and determines the orbit for each tracked RSO using minimum variance differential correction methods [9]. This digital model includes the High-Accuracy Catalog (HAC) of the 18 SDS, which is updated multiple times daily as the orbit determination process proceeds [9]. The **Data & Epoch Synchronization** FE, derived from the **Synchronization FE**, ensures that RSO state estimates are well aligned in time and interpolates between ephemeris points to align epochs for the purposes of conjunction assessment [9]. The **Mission Control Visualization** FE, derived from the **Presentation and Representation FE**, enables 18 SDS & 19 SDS operators to visualize the LEO RSO environment in mission control rooms within the Combined Space Operations Center (CSpOC) in the Vandenberg Space Force Base in California, where 18 SDS is located, and within the Naval Support Facility Dahlgren in Virginia, where 19 SDS is located [28–30]. Lastly, the **Software & Catalog Maintenance** FE, derived from the **Maintenance FE**, represents the various processes used to maintain the various software elements in the DTE, including the Space-Track application and the HAC.

The updated HAC provides the necessary inputs for the **Simulation & Orbit Propagation** FE, derived from the **Simulation FE** within the Application and Service Sub-Entity, in which the 18 SDS uses the Simplified General Perturbations Model 4 (SGP4) analytical model and the Special Perturbations (SP) numerical method to propagate the orbits of its tracked RSOs [31]. The predicted RSO trajectories are then screened against one another by the 19 SDS in the **Data Analysis & Conjunction Detection** FE, derived from the **Analytic Service FE** [9]. The Super Computation of Miss Between Orbits (COMBO) software identifies potential conjunctions and generates CDMs as part of the **SuperCOMBO Report & CDM Generator** FE, which is itself derived from the **Reporting FE** of ISO 23247 [9]. These reports are uploaded to the **Space-Track Application**, which serves as the service-providing **Application Support FE**, automatically making SSA info, CDMs, and CANs available to the relevant users within the UE.

The **Resource Access and Interchange Sub-Entity** of Fig. 2 is abbreviated in both name and capability as the **Resource Access Sub-Entity** in Fig. 4. The **Access Control FE** is resolved into an **Account Credentials Access Control System**, used to ensure that only authorized users are accessing Space-Track and operating the digital twin, and a **Classified Access Control System**, to ensure that classified information is shared only through secure communication channels among individuals with appropriate clearances [9]. However, the other three FEs of the Resource Access and Interchange Sub-Entity are either unimplemented or nonessential for this application (for now). The **Interoperability Support FE** is used to ensure that the various blocks within the digital twin are mutually cohesive, especially in applications involving diverse commercial-off-the-shelf FEs [6]. Since the existing on-orbit collision avoidance process was developed outside of an explicit digital twin framework over the course of decades, many of the tools being used in this process were developed specifically for this application, with interoperability built in as a feature [9, 24, 25]. Similar logic applies for the **Plug-and-Play Support FE**, which is useful for applications in which individual FEs may be swapped in and out in a modular fashion to increase the versatility of the digital twin [6]. The **Peer Interface FE**, on the other hand, enables the digital twin to interface with other digital twins in related applications [6]. As the intersection between on-orbit collision avoidance systems and standardized digital twins is still nascent, no such interface is present at the time of this writing. However, this may be implemented at a future date if additional processes—and associated digital twins—for space situational awareness are developed and matured over the coming years. This possibility is explored in more detail in Section IV.

The generic **User Interface FE** in the ISO 23247 standard architecture is resolved into four distinct FEs, each with a distinct role, in Fig. 4. Although their roles are distinct in practice, **18 SDS & 19 SDS** are represented by a single FE for simplicity. Of the two, 18 SDS is generally responsible for maintaining space situational awareness, maintaining the HAC, and tasking the SSN sensors under its purview, among other activities not discussed in this report for brevity [9]. The 19 SDS is generally responsible for performing conjunction assessments using the 18 SDS HAC and O/O-provided ephemerides and uploading related files to the Space-Track application, among other tasks [9]. Many of these processes are automated and, accordingly, captured within the DTE [9]. In addition, **Collaborative O/Os** may provide S/C ephemerides and maneuver notifications to 18 SDS & 19 SDS through the Space-Track application [9]. Both Collaborative O/Os and strictly **Cooperative O/Os** may send control commands to their respective spacecraft upon receipt of a CDM or CAN [9]. **Public Users** may also take advantage of this publicly available information for various reasons, including scientific research and general interest [22].

As with the DTE, the mapping of the CSE FEs across application domains is reasonably straightforward. For the on-orbit collision avoidance application, the **Data Translation FE** of ISO 23247, which translates data exchanged between entities [21], maps to the **19 SDS Conversion Utility Software**, which converts O/O-provided ephemerides into formats that are compatible with one another, the HAC, and SuperCOMBO [9]. The **Data Assurance FE**, which verifies data integrity and accuracy [21], maps to the **Data Assurance & Formatting** FE. The function of this entity is primarily supported through rigorous data formatting standards supplied in Ref. [9]. If files are improperly formatted or named incorrectly, or if data within the files have incorrect notation or units, then Space-Track will reject the inputs and return error messages accordingly [9]. Finally, the **Security Support FE**, which ensures access authentication, integrity, authorization, and confidentiality [21], maps to the **Cybersecurity & Network Protection** FE, which represents the data and access security functionalities distributed throughout the digital twin.

Now that this prescriptive aerospace process has been formally represented in a DTF, the resulting framework can be adapted to other, related aerospace applications, effectively functioning as a bridge between the *ad hoc* approaches historically used in the aerospace industry and the more standardized and consistent approaches recommended by the AIAA Digital Engineering Integration Committee to increase widespread adoption of digital twins in the field [5]. Frameworks for novel or nascent processes and applications are especially valuable, as they can be used to guide the development of those processes and their functional elements from an early stage, as will be discussed in Section IV.

IV. Descriptive Digital Twin Framework for Space-Based Orbital Debris Detection

As mentioned in Section I, recent advancements in space-based RSO sensing and state estimation capabilities have promoted discussions regarding leveraging on-orbit satellites for improving overall space situational awareness [11, 13–18]. Ref. [17], in particular, suggests that existing commercial optical sensors onboard thousands of active satellites have the potential to enable opportunistic detection of sub-10-cm-class orbital debris on a massive scale. The capability of individual spacecraft to use optical sensors to track anthropogenic RSOs—traditionally, those larger than 10 cm in characteristic length—was first demonstrated on orbit by the Midcourse Space Experiment (MSX) via the Space-Based Visible (SBV) sensor [32]. Although the MSX was retired in 2008 [33], since then, the SSN has augmented its space-based RSO-tracking capabilities with assets like the SBSS system [34] and the Canadian Sapphire satellite [19].

Thus, precedence for space-based space surveillance for larger RSOs has been established; however, in order to detect, catalog, and track the estimated hundreds of thousands of 1-cm to 10-cm RSOs in LEO [8], a more standardized process—and a more formal framework—will be required. Accordingly, this section seeks to establish a space-based debris detection digital twin framework with *descriptive* functionality, seeking to represent the current state of sub-10-cm-class RSOs in the LEO space environment. This will serve as the foundation for the development of space-based debris detection digital twins with progressively more advanced functionalities—namely, diagnostic, predictive, prescriptive, and intelligent.

A. High-Level Digital Twin Framework

Figure 5 seeks to capture the proposed descriptive process for space-based detection of sub-10-cm-class debris in a high-level digital twin architecture that emphasizes, as in Fig. 3, the major entities, their sub-entities, and the information exchanged among them through the various digital twin networks. As before, additional information concerning the FEs is provided in the next subsection.

Of particular note is the fact that the major entities and sub-entities—as well as the color scheme—are shared across Fig. 3 and Fig. 5. However, the role of each entity and the information exchanged among the entities have evolved in the adaptation process. For example, in this framework, the Controllable LEO Resident Space Objects would receive scanning maneuver schedules from the Cooperative S/C Control Sub-Entity, based on sensor tasking commands sent by Collaborative O/Os, and leverage these maneuvers to collect debris scan data from the Uncontrollable LEO Resident Space Objects. The Controllable LEO RSOs would transmit the collected RSO position and velocity data, as well as their own position and velocity data, to the Collaborative S/C Data Collection Sub-Entity using radio frequency or optical communication transmitters in contact with ground station terminals [20]. Collaborative O/Os would receive these data and upload corresponding ephemerides for both their S/C and their observed RSOs to the DTE, the roles of which are discussed in greater detail in the next subsection.

With regards to the UE, it is assumed that Collaborative O/Os, in the interest of preserving their own space assets and the LEO space environment in general, are willing to share their S/C and RSO ephemerides with the same set of collision avoidance stakeholders participating in or benefiting from the existing prescriptive process. Thus, 18 SDS & 19 SDS, Public Users, Cooperative O/Os, and other Collaborative O/Os would all have access to the SSA info and reports that are generated by the DTE. The 18 SDS & 19 SDS may also use the DTE to upload files and exchange information with the other DTE users in the UE.

It is likewise worth noting that some network arrows from Fig. 3 are not relevant to Fig. 5. For example, in honor of the focus on space-based debris detection by sensors outside the purview of the SSN, the Observable RSO Data Collection Sub-Entity in Fig. 5 does not receive sensor tasking commands from the 18 SDS & 19 SDS, collect RSO position and velocity data from the Observable LEO RSOs, or transmit processed RSO position and velocity data to the Operation and Management Sub-Entity. As this strictly descriptive digital twin architecture does not include predictive or prescriptive functionalities, the DTE would not generate CDMs or CANs for relevant users, and O/Os would not send commands for COLA maneuvers to the Controllable LEO RSOs through the Cooperative S/C Control Sub-Entity or provide the associated maneuver notifications through the DTE.

Finally, the CSE in this architecture operates in a capacity similar to the CSE from the prescriptive architecture discussed in Section III.

B. Mapping of Functional Entities

Figure 6 offers a lower-level visualization of the individual FEs embedded within the major entities and sub-entities in Fig. 5. Given that Fig. 6 is effectively derived from—and shares a color scheme with—Fig. 4, the goal of this section is to identify key formal and functional differences among the FEs embedded within the two frameworks.

To begin, since a large-scale process for space-based debris detection is yet to be developed, many of the FEs in Fig. 6 are genericized from their counterparts in Fig. 4. For example, within the DTE, the **Mission Control Visualization** and **Space-Track Application** FEs specific to 18 SDS & 19 SDS are replaced with the more generic **Visualization Software** and **Web-Based SSA Application** FEs, respectively, that would offer very similar functionalities. Likewise, within the CSE, the **19 SDS Conversion Utility Software** and **Data Assurance & Formatting** FEs are replaced with **Data Translation FE** and **Data Assurance FE**, respectively.

Since the focus of the application is space-based detection of sub-10-cm-class RSOs, the FEs within the Observable LEO RSOs entity have been updated accordingly. The Uncontrollable LEO RSOs sub-entity includes only **Small Debris (< 10 cm)**, and the Controllable LEO RSOs sub-entity emphasizes **Collaborative O/O Spacecraft**. As defined in Section III, strictly Cooperative O/O Spacecraft would not be expected to collect or share information on their local RSOs or to maneuver in response to a CDM or CAN in a strictly descriptive digital twin. However, the Collaborative S/C Data Collection Sub-Entity now includes a **Space-Based Sensors** FE to account for the Collaborative O/O Spacecraft sensors collecting data on Small Debris (< 10 cm).

Similarly, for this application, the functionality of the Observable RSO Data Collection Sub-Entity is significantly reduced, with the U.S. Space Surveillance Network FE and corresponding Data Collection and Storage and Data Processing FEs having no counterparts in Fig. 6. The **RSO Identification & Track Correlation** FE, which is required for identifying the individual debris objects and correlating tracks from thousands of S/C sensors [17, 25, 26, 35], could

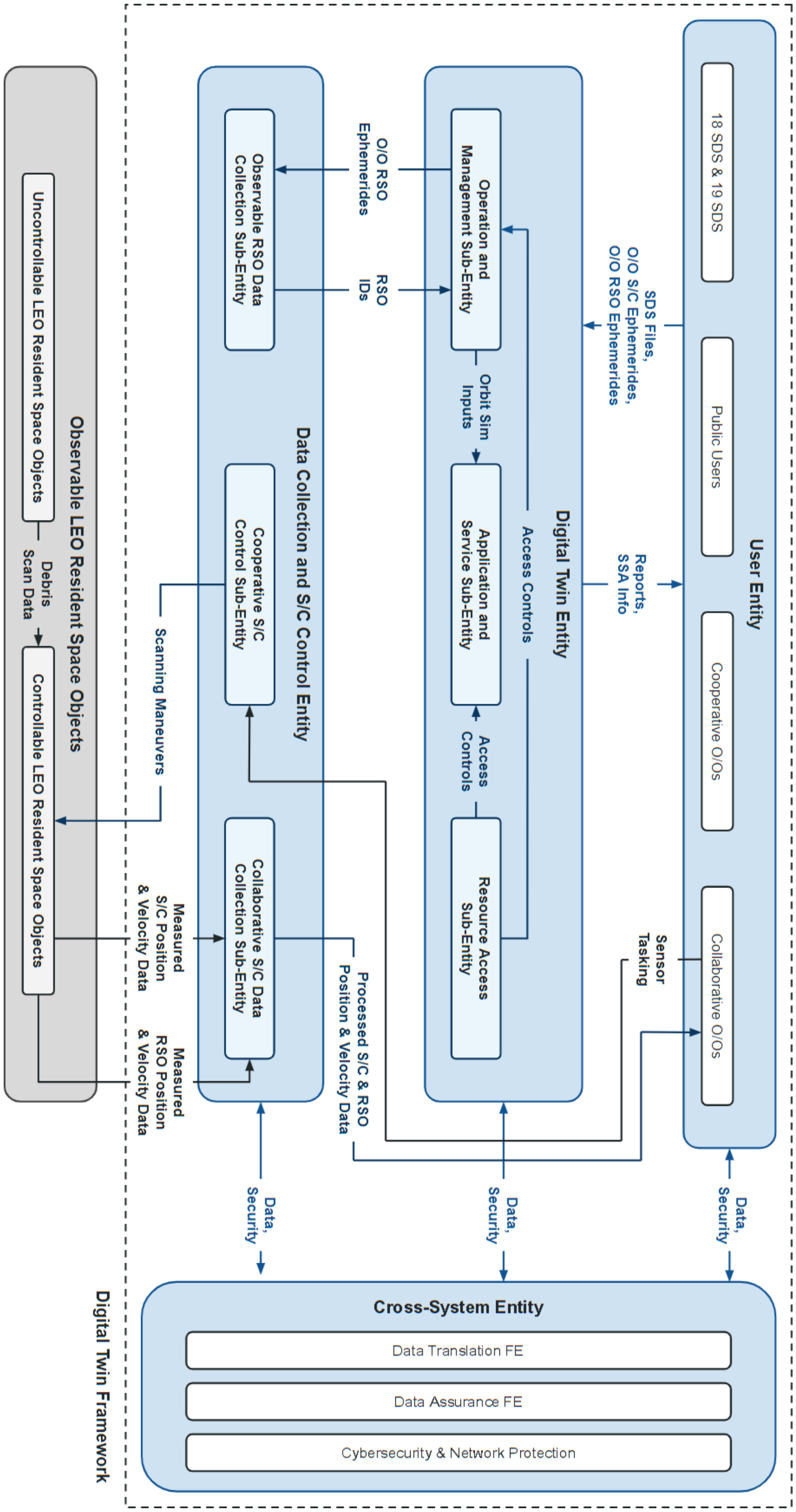

Fig. 5 A higher-level descriptive digital twin architecture for space-based orbital debris detection, with a focus on the information exchanged among major entities, sub-entities, and functional entities.

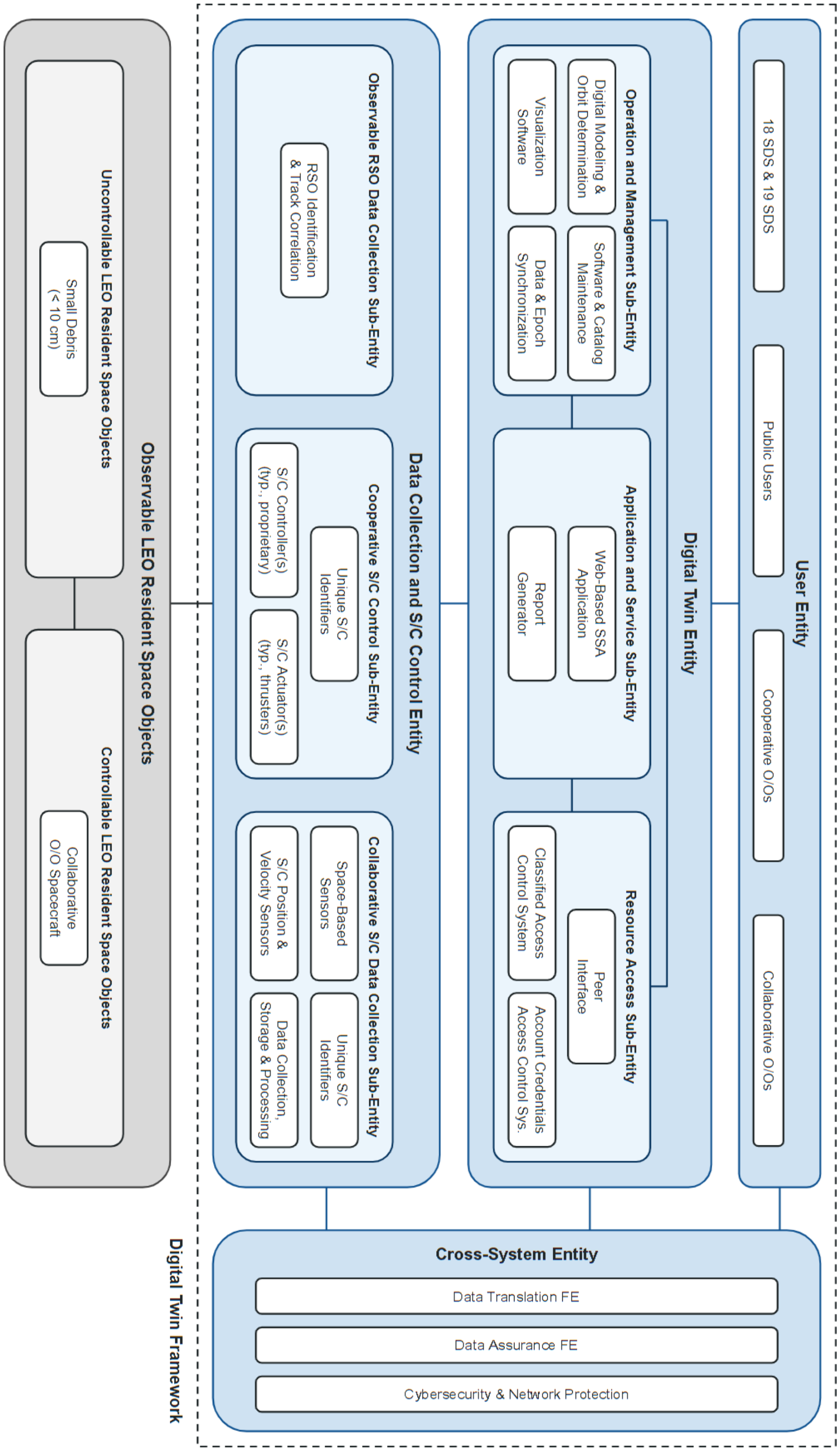

Fig. 6 A lower-level descriptive digital twin architecture for space-based orbital debris detection, with a focus on enumerating the functional elements constituting the entities and sub-entities.

have reasonably been placed within the DTE without loss of generality or function. However, to maximize consistency with Fig. 4, the RSO Identification & Track Correlation FE is captured within the Observable RSO Data Collection Sub-Entity. Consequently, the Operation and Management Sub-Entity, after receiving O/O RSO Ephemerides from Collaborative O/Os, passes them to the Observable RSO Data Collection Sub-Entity, wherein the RSO Identification & Track Correlation FE processes the provided data and returns unique RSO IDs to the DTE.

Beyond this, the outputs of the Operation and Management Sub-Entity—that is, the required inputs for an orbital simulation—are largely the same in both cases. However, due to the absence of any propagation and prediction functionalities in a strictly descriptive digital twin, the Simulation & Orbit Propagation and Data Analysis & Conjunction Detection FEs from Fig. 4 have no counterparts in Fig. 6. Likewise, the **SuperCOMBO Report & CDM Generator** of Fig. 3 is reduced in scope to a generic **Report Generator**, which would upload reports to the Web-Based SSA Application to make SSA info available to authorized users. However, the **Digital Modeling & Orbit Determination** FE persists, as it is essential for determining the current state of sub-10-cm-class RSOs in the LEO space environment [9]. Since the scope of this DTF is intentionally limited to descriptive functionality, the adaptation of any FEs from Fig. 4 that offer higher functionality is relegated as future work.

Finally, the Resource Access Sub-Entity now includes a **Peer Interface** FE, which previously appeared in the ISO 23247 architecture of Fig. 2 but was not included in the prescriptive architecture of Fig. 4. As mentioned in Section III, the Peer Interface FE enables interactions with other digital twins. For this application, this would allow a digital twin derived from the descriptive DTF for space-based orbital debris detection, as described in this section, to share information with a digital twin derived from the prescriptive DTF for on-orbit collision avoidance, as described in Section III, enabling further improvement of overall space situational awareness and on-orbit collision avoidance systems.

Although the scope of the descriptive DTF presented in this section appears limited in comparison to the prescriptive DTF presented in Section III, it is important to note that the former is novel, whereas the latter describes a process that has existed in various forms for many years [9]. As the space-based debris detection DTF matures and encapsulates additional functionalities over the years, the scope of the two frameworks presented in this report will grow to be comparable.

C. Representative Use-Case

As mentioned in Section I, the number of active satellites in LEO has increased dramatically in recent years [7]. A significant source of this proliferation is mega-constellations of spacecraft providing satellite internet services [7]. Suppose that a particular satellite internet provider—one of the Collaborative O/Os—has hundreds or thousands of microsatellites—Collaborative O/O Spacecraft—distributed across a variety of orbits between 500 km and 600 km in altitude above Earth's surface. By design, each of these satellites has at least two optical Space-Based Sensors known as star trackers, which are nominally used to determine the attitude of the spacecraft by capturing images of distant stars and comparing them to onboard star catalogs [13]. Incidentally, these images also often capture adequately illuminated RSOs that are nearby and within the star tracker's field of view [13, 17]. In particular, when the star trackers are not actively being used for attitude determination, they can be used to passively collect SSA data on sub-10-cm-class RSOs within 50 km of the satellite [17]. Consequently, the constellation as a whole can collect SSA data for RSOs in this size regime for altitudes between 450 km and 650 km above Earth's surface.

Several times per day, these spacecraft can use radio frequency waves (e.g., UHF-band, S-band, X-band, etc.) [20] to transmit collected star tracker images (and associated time, position, velocity, attitude, and angular velocity data [35]) to compatible commercial radio frequency antennas on Earth's surface [20]. The amount of data satellites can transmit along space-to-ground links is often limited by technical capabilities, licensing regulations, and environmental conditions [20], so their respective O/Os may choose to downlink only a subset of the collected star tracker images, informed possibly by requests from the 18 SDS & 19 SDS, during a given ground contact opportunity. In any case, the downlinked images are then processed on ground-based computers using techniques such as those described in [36] for streak detection, [37] for light modeling and space object classification, and [14] and [15] for RSO state estimation.

The development and deployment of these and other data processing algorithms for star tracker images of incident RSOs are areas of ongoing research. In fact, recent advances in onboard RSO state estimation suggest that, in the near future, spacecraft may be able to use their onboard computer(s) to efficiently estimate the position and velocity of RSOs captured in their star tracker images [35]. If this is realized, instead of transmitting a small number of comparatively large image files, spacecraft with such capabilities would be able to transmit smaller sets of pre-processed RSO SSA data for a larger number of RSOs, further increasing the value provided by space-based space surveillance [35].

Once processed, these data are ingested into the Digital Twin Entity for modeling and visualization of the partial LEO RSO environment, as it pertains to sub-10-cm-class RSOs. As users of this digital twin, the 18 SDS & 19 SDS can access and ingest these SSA data through the Web-Based SSA Application and, per the existing prescriptive collision avoidance process, provide CDMs and CANs to Cooperative O/Os and Collaborative O/Os, as required [9]. This cycle continues indefinitely, substantially improving the U.S. government's awareness of the space domain in this region of LEO and its corresponding ability to prevent in-space collisions with small debris particles therein.

V. Conclusion

In response to recommendations by the AIAA Digital Engineering Integration Committee encouraging the development of standard digital twin reference models for aerospace applications [5], this paper has proposed—and demonstrated the feasibility of—adapting existing digital twin standard frameworks from other application domains for aerospace applications. In particular, the ISO 23247 standard for digital twins in manufacturing has been adapted for the first time to a non-manufacturing aerospace application—on-orbit collision avoidance. The well-established process involving the U.S. SSN, 18 SDS, and 19 SDS for on-orbit collision avoidance in LEO has been captured within a prescriptive digital twin framework that seeks to represent the LEO RSO space environment.

This architecture for an established process is, in turn, adapted for a similar, novel application involving sub-10-cm-class orbital debris detection by on-orbit satellites, which continues to be an active area of research [17, 18]. Although the focus is on sub-10-cm-class debris, the (currently) descriptive digital twin framework can be expanded to include space-based measurements for RSOs of any size or class and can even be combined with ground-based frameworks to be used in generating a more comprehensive digital twin of the LEO space environment. It is worth noting that the number of sub-10-cm-class debris in LEO is estimated to be in the millions [8] and that the techniques for processing space-based sensor images for RSO data can be computationally expensive [14, 15, 35–37], so a digital twin seeking to represent this many RSOs may encounter computational limitations. However, if sensing capabilities and computational power allow, digital twins derived from this framework can even be extended beyond LEO to geosynchronous altitudes or higher.

This work offers a novel approach for the standardization of digital twins in the aerospace industry based on already-published standards and serves as a foundation for the development of formal digital twins with applications in space-based orbital debris detection and collision avoidance. A digital twin derived from the descriptive framework presented in this paper can be augmented over time to offer increasingly sophisticated functionalities—diagnostic, predictive, prescriptive, and intelligent—through the integration of additional digital and physical elements. For example, integration of the sub-10-cm-class debris data offered by a descriptive debris detection digital twin with the baseline data in the SSN RSO catalog would augment the capabilities and value of the existing prescriptive collision avoidance process. With additional effort, a layer of artificial intelligence could be added to enable a satellite within a cooperative network of satellites to autonomously correct its trajectory to avoid a debris particle detected by another satellite within the same network.

The result is a roadmap from a basic (but useful) descriptive model that focuses primarily on sub-10-cm-class debris detection and monitoring to an intelligent system that enables autonomous collision avoidance within a satellite network. Moreover, encoding these architectures into formal standards is expected to promote top-down adoption of digital twin technologies in the satellite industry, encourage informed space traffic management policy efforts, and reduce the labor burden on the SSN, 18 SDS, 19 SDS, and other relevant U.S. government agencies. Thus, the development and standardization of each of these frameworks is the subject of future work.

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