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Mastering Complexity for Indoor Inspection Drone Development

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***Abstract*—Drones have successfully been used for many outdoor uses, notably inspection of buildings. Using drones for indoor inspection of buildings raises new design challenges, in particular with respect to Building Information Modeling and indoor navigation issues since satellite-based localization does not work inside a building. The authors of this paper advocate for using a Systems Engineering approach to address these design challenges. The paper surveys systems engineering methods published in the literature and addresses a method adapted to complex systems which are subject to evolving environment such as drones for indoor inspection of buildings. The chosen method provides several views of the system from a global perspective including mission and operational analyses, to more specific perspectives including requirement, functional, logical and physical analyses.**

***Index Terms*—Systems Engineering, Method, Drone, Building Indoor Inspection, BIM.**

I. INTRODUCTION

Over the past few years, drones have increasingly been used in transportation, logistics or agriculture to achieve various missions such as firefighting, safety, surveillance, generation of climate data, to name a few [1]. In building industry, drones have been used to inspect the facade of high-rise buildings that raise safety risk and danger to Humans [2]. In [3] Anwar, Izhar, Muhammad, and Najam use a drone to monitor a construction site by creating a 3D model at various construction stages. Following decades of using inspection tools based on manual or semi-automated techniques, the building industry can now take many advantages from drones, that are expected to provide time-efficient and cost-effective operations [4], relying on sensors that offer precise results.

So far, inspection drones have mostly been used for outdoor inspections of buildings. By contrast, little work has been published on drones for indoor inspections of buildings. Using drones for indoor inspection of buildings raises new design challenges, especially navigation issues since satellite-based localization does not work inside a building [5], or access to rooms with closed doors. Further, operating within unknown and confined environments such as the interior of an existing building increases the complexity of the mission.

The complexity level reached by indoor inspection drones leads the authors of this paper to propose a Systems Engineering (SE) approach to address the design of these drones. Systems Engineering is an interdisciplinary approach enabling the successful design of engineered systems according to the needs of all the stakeholders involved throughout the system life cycle [6]. From the definition of customer needs and desires, SE addresses the system from various viewpoints to completely and accurately design the system. The benefits of adopting SE approach are clearly highlighted in the literature [7], [8]. SE enables an effective collaborative work between the engineering teams [9] as well as managing the increasing complexity of today's systems as technology is rapidly progressing [10]. SE approach addresses the system from the necessary comprehensive perspectives allowing the implication of all involved stakeholders in the decision-making process [11].

Applying a SE approach requires the adoption of a well-defined method to guide the system engineer through the development of the system. In [12] Brazier, van Langen, Lukosch and Vingerhoeds propose a revised version of the Generic Design Model [13] made up of four design sub-processes: requirements design, artefact design, design process coordination, and simulation, experimentation and implementation. This method encompasses the mission statement, the capture of the needs and the desires of all the involved stakeholders from which requirements will be defined and qualified. The method can be adapted to consider the system from different perspectives, especially operational, functional, logical and physical, to enhance the understanding of the system.

The paper is organized as follows. Section II reviews the current building inspection practices and justifies the need for enhancing indoor inspection systems. Section III surveys related work on Systems Engineering methods. Section IV presents the SE method which is used in this paper. Section V presents its application to the indoor inspection drone. Section VI provides discussion on the results and presents the future work. Section VII concludes the paper.

II. NEED FOR ENHANCING INDOOR INSPECTION SYSTEMS

Inspection activities are carried out during the exploitation life of a building to ensure the safety and security of its users. Inspections concern the building sites themselves as well as monitoring the construction progress. Current techniques are mostly based on hand-held and terrestrial tools [4], or even direct visual inspection to detect building defects. Thermal cameras, which detect infrared radiation emitted from object's surface, are used to detect energy-related problems especially heat loss, air leakage and moisture [14], as well as cracks and erosions on surfaces [15]. The thermographer walks through the building to capture thermal images of the building element or system to be inspected.

In [16] Bortolini and Forcada use mobile techniques combining photos and text or voice annotations to detect and describe the building defects. These techniques rely on smartphone's cameras and mobile applications such as *Pick & Go* [17], *Inspect Anything* [18] and *Pocket Inspections* [19].

These technologies are applicable for both indoor and outdoor inspections, however they are still tedious and time consuming since they require the presence of Humans in field to perform the inspections. Further, they are limited to only items that are accessible to people to minimize safety risks during the inspection.

Building industry can now take many advantages from drones in contrast with traditional inspection tools which are based on manual or semi-automated techniques. Drones are indeed expected to provide time-efficient and cost-effective operations [4]. So far, drone-based inspections have mostly been used for outdoor purpose. In [2] Duque, Seo and Wacker summarize findings on current visual-based inspection, monitoring, and analysis of infrastructures using drones. Drones are used to detect critical cracks and erosion especially on high-rise buildings facade [20], [21].

On the other hand, the building industry is processing a digitization of its processes thanks to the implementation of the Building Information Modeling (BIM). According to the European Union BIM Task Group [22], 'BIM is a digital form of construction and asset operations. It applies to new build projects; and crucially, BIM supports the renovation, refurbishment and maintenance of the built environment – the largest share of the sector'. BIM models contain both geometrical and semantic information [23]. Geometric information includes dimensional and spatial data; and semantic information consists in descriptive and procedural characteristics, description of the relationships between the objects of the model, as well as technical properties of the materials (such as mechanical, thermal and acoustic performances). The inspection of buildings can rely on BIM models since they provide information that can be used to manage the maintenance and renovation activities on existing buildings during their exploitation life [24].

In this paper, we propose an indoor inspection drone to address the lack of efficient inspection means to evaluate the health of buildings. Drones are chosen since they allow significant time and cost-saving operations, as well as a high flexibility to access hard-to-reach areas which compromise the safety of Humans.

An operator supervises the drone to perform safely and correctly its mission from a ground station which is posted at the foot of the building to be inspected. The drone is intended to collect building information which will be used to inspect both building elements and systems:

- Building elements include structural ones, such as walls, beams, columns, foundations, roofs and floors; as well as non-structural ones which are doors, windows, furniture, stairs, ceiling and floor coverings.
- Building systems include electrical, heating, ventilation and air-conditioning (HVAC), plumbing, elevator, and fire protection systems.

Disorders in building elements are often visually easy to detect [16], for instance superficial cracks in structural elements which are usually due to mechanical phenomena such as shrinkage or the differential movement of the bricks and bearing structures composing the element [25]. In addition, the drone detects surface moisture and vegetation growth which are mostly due to varied phenomena related to damp coming especially from the construction materials used in the building element, or from the rainwater and the condensation.

Regarding the building systems, water leakage on the plumbing system can be identified, which represent the most important percentage of the home insurance claims in France (38% in 2017) [26]. Additional defects related to the safety and the comfort of the users are considered, such as damaged insulation and unsafe sockets on the electrical system, as well as corroded parts and leaks on the HVAC and the fire protection systems. Most of these defects are not visually identifiable since they are concealed in the walls or hidden behind other building elements.

Using drones for indoor inspection raises new design challenges, especially to rely the inspection on BIM, and navigation issues in unknown and confined environment which is continuously evolving with the time. The accessibility in building is by itself a challenge: opening closed doors and windows, move through stairs, avoid furniture, rubbles, etc. Further, such an indoor inspection drone is often embedding multiple, varied payload and therefore massive carrying capacity compromising its energy efficiency and even the flight range. Designing such an inspection drone implies to deal with numerous complex requirements. To master that complexity, one needs to adopt a general approach that encompasses all the aspects of the system throughout all the stages of its life cycle which is the case of the SE approach.

III. SYSTEMS ENGINEERING METHODS

According to the International Council on Systems Engineering (INCOSE), 'Systems Engineering (SE) is a *transdisciplinary* and integrative approach to enable the successful *realization, use* and *retirement* of engineered systems, using systems principles and concepts, and scientific, technological and management methods' [6]. Applying a SE approach relies on a structured method to guide the system engineer through the development of the system.

In [12] Brazier, van Langen, Lukosch and Vingerhoeds propose a structured systems design and engineering approach made up of four design sub-processes: requirements design; artefact design; design process coordination; and simulation, experimentation, and implementation (see also section IV-B). The method presented in [12] encompasses the mission statement followed by the capture of the stakeholder needs and desires which are translated into requirements. It also includes a logical analysis, and studies the structure of the system, considering its subsystems and their interdependencies. The authors describe their method to be suitable to evolving complex systems such as autonomous vehicles.

In [10] Apvrille, de Saqui-Sannes and Vingerhoeds introduce a method applicable to the development of a broad variety of real-time systems. The method is associated with free SysML [27] tool TTool [28]. It starts with the capture of the modeling assumptions which allow iterative and incremental modeling (starting with a simplified model merging to a more realistic one). Each iteration of the method includes assumptions and requirements capture, analysis, design, simulation and verification. A drone serves as case study to demonstrate the interest of the simulator and the model checker of TTool for early detection of design errors in the life cycle of systems.

In [29] Fei, Bin, Rui and Shunhua propose a six-step method covering modeling planing and organization, capture of the stakeholders' needs and definition of the requirements, synthesis of alternative system architectures, integration, and verification and validation (V&V) activities. The method proposed in [29] is applied to the Full Authority Digital Engine Control (FADEC) system. The authors claim their method can help designers and engineers to develop complex systems in a consistent manner.

In [30] Li, Verhagen and Curran present an architecture design method incorporating the RFLP views: Requirements, Functional, Logical and Physical. These views detail the system requirements, the system functions, the system behaviors and the physical items, respectively. The authors apply the method to build a functional architecture of a Prognostics and Health Management (PHM) system. This method considers system requirements as inputs, and ignores mission definition and stakeholders' needs. It provides several views that enhance the understanding of the system. These views consider the representations of the system from a behavioral and an organizational perspective.

In [31] Hernandez and Fernandez-Sanchez present a method for the development of a collaborative robotic system. It has five main steps: identify operational scenarios, specify system capabilities and high level functional requirements, specify quality attributes and system non functional requirements, create system functional and physical architectures. This method facilitates the reuse, the maintenance and the scalability of the robot capabilities and functional interfaces as the robot industry implies constantly new applications presenting new challenges. Compared to previously cited methods, this approach provides an operational view identifying the operational needs and related operational scenarios which can be considered for the design of a drone.

In [32] Spangelo, Kaslow et al. propose a method for CubeSat systems, based on the Object Oriented Systems Engineering Methodology (OOSEM) from the INCOSE. OOSEM is a system-level development method combining object-oriented concepts with systems engineering practices. It starts with the mission definition, and includes requirements analysis, logical and allocated architecture design, guidance for trade studies, verification and validation activities [33].

These SE methods highlight complementary concepts needed to describe systems, including mission, needs and requirements, operations, functions, behaviors, structures and architectures. These concepts allow one to consider the system throughout all the stages of its life cycle, which improves the understanding and the quality of the results. Further, the use of models to support the development can be considered, that is applying Model-Based Systems Engineering (MBSE). MBSE is expected to improve system design in terms of completeness, process, integrity, accuracy, maturity, performance, and clarity [7]. The next section presents the SE method that is used in this paper to address an indoor inspection drone.

IV. SYSTEMS ENGINEERING METHOD FOR AN INDOOR INSPECTION DRONE

The systems design and engineering approach presented in [12] is suitable for complex systems which are subject to continuously evolving environment such as indoor inspection drones.

A. Qualitative criteria

Relying on the SE methods presented in the previous section, we may enumerate qualitative criteria in order to adapt the method presented in [12] which is used in this paper to manage the complexity of the development of an inspection drone. The method shall:

- *C1: start with the mission definition*, because the mission makes one drone different from others. C1 includes the capture of the customer's initial needs and the formalisation of the problem expected to be solved by the system [34].
- *C2: address the needs from all the involved stakeholders* at each stage of the system's life cycle. C2 allows to consider the entire system from its genesis to its end [35].
- *C3: consider the requirement analysis*. C3 includes the definition of stakeholders' requirements which are derived from their needs and will be translated into system requirements [12].
- *C4: support the traceability of the requirements* along the development process. The requirements can be refined as much as we go further into the design of the system (iteration) [10].
- *C5: address an operational view of the system*. C5 allows to consider the behavior of the system within its opera-

tional environment including all the possible operational concepts and modes [35].

- *C6: address a functional view of the system.* C6 allows to consider the functions, that are tasks, actions or activities to be performed by the system to achieve its intended mission [36].
- *C7: address a logical view of the system.* C7 allows to study the behavior of the system to propose a preliminary system architecture [36].
- *C8: address a physical view of the system.* C8 allows to design a physical architecture of the system containing the physical components and subsystems [36].

On the basis of these criteria, the method presented in [12] can be adapted to encompass comprehensive and complementary viewpoints for a complete and an accurate design of an inspection drone.

B. Adopted Systems Engineering method

The method adopted in this paper is based on the systems design and engineering approach presented in [12] which is made up of four sub-processes. *Requirements design* translates the stakeholder needs and desires into requirements. *Artefact design* describes a design object according to the requirements provided by the requirements design. *Design process coordination* focuses on the determination of the design strategy, including the progress of the design process and the allocation of resources. *Simulation, experimentation and implementation* allow one to assess the feasibility of the defined requirements and/or design, and facilitate the exchanges with the stakeholders. These sub-processes are active in parallel for each of the stages of the system's life cycle to cope with the continuous evolution of the system and its environment. Hence existing requirements have to be adapted and new ones can be specified since stakeholder needs and desires evolve during the system's life cycle.

This is an iterative, seven-step method which is satisfying the set of criteria presented in previous subsection.

1) Mission Analysis: defines the purpose, the mission and the objectives of the system to be developed to solve the problem which is identified from the initial needs expressed by the customer. The purpose justifies the existence of the system whereas the mission expresses the set of services it provides [34]. Initial objectives can be formulated to quantify the mission. These characteristics can be refined as much as needed during all the design process.

2) Requirement Analysis: includes the capture of the needs of stakeholders and their translation into system requirements. Stakeholder needs and desires are captured to define correctly their expectations on the system. The stakeholders can be classified into 4 categories according to the typology proposed by the 'Association Française de l'Ingénierie Système' (AFIS), the French association of systems engineering in [37]:

- The acquirer side who will be concerned by the use of the system,
- The supplier side who will be implied in the realization of the system,
- Potentially concerned parties who will be more or less directly impacted by the system,
- Regulatory bodies, such as certification and standardization agencies.

These needs and desires of stakeholders are interpreted and translated into stakeholder requirements and then into system requirements afterwards [38]. Requirements can be qualified into functional, structural, behavioral and experiential [12].

- Functional requirements consist in the functions provided by the system.
- Behavioral requirements consist in the desired behavior of the system.
- Structural requirements concern the components of the system and their relationships.
- Experiential requirements concern the effect of the use of the system in the real world.

3) Operational Analysis: aims to study the behavior of the system within its operational environment to deliver its intended services. Operational Analysis addresses the operational concepts describing the characteristics of the system from the operator's viewpoint to identify the system context and interfaces [36]. The different operational modes are studied to consider all the possible operational situations of the system throughout all its operational life.

4) Functional Analysis: identifies the functions and subfunctions of the system to satisfy the previously defined system requirements. The aim is to identify the functions and services that the system has to provide, independently of any technical solutions or technological choices, and their interfaces to build a functional architecture of the system.

5) Logical Architecture Analysis: translates the functional architecture into logical architecture. Logical Analysis focuses on decomposing the system into logical elements to design a preliminary system architecture [36]. The functions are allocated to logical elements which can be some available technical solutions, subsystems or components, but being identified at high level.

6) Physical Architecture Analysis: focuses on designing the physical architecture of the system from the previously defined functional and logical architectures. It is composed of physical components with a given set of properties, and their physical interfaces to which the functions are allocated to describe how will the system be implemented.

7) Verification & Validation: are transverse activities to every life cycle stage of the system. They can be applied to every engineering element that has contributed to the definition of the system itself (operations, requirements, functions, data flow, system elements, interfaces, and design properties). The purpose of $Verification$ is to provide evidence that the 'product is built right', while $Validation$ is intended to ensure that the 'right product is built'. [36].

V. APPLICATION TO AN INDOOR INSPECTION DRONE

In this section, the SE method presented in the previous section is applied at a high level of abstraction to the indoor inspection system of an existing building.

A. *Mission Analysis*

From the stated problem that the indoor inspection system is intended to solve as presented in section II, we can define its purpose, its mission, and initial objectives to have a vision on the way forward.

- **Problem**: There is a lack of efficient inspection systems for the interior of an existing building today which makes the operations tedious and costful.
- **Purpose**: The system provides a cost efficient and time saving solution to inspect the interior of an existing building.
- **Mission**: The system collects valuable building information from the interior of an existing building in order to detect disorders both on building elements and systems.
- **Objectives**: Initial objectives are as follows:
  1) The system detects disorders of the building especially cracks more than 1mm of large; water leakage causing surface moisture, vegetation growth and corrosion.
  2) The system reduces the inspection time and the workload by at least 30% compared to the conventional means.

B. *Requirement analysis*

Involved stakeholders during all the stages of the system life cycle are as follows:

- Acquirer side: Building owner, Building inspection specialist, Civil engineer, Operator.
- Supplier side: System engineer, Hardware and software developer, System integrator, Supplier, Maintenance staff, Trainer.
- Building related instances: Resident, Building worker, Health and Safety Committee.
- Regulatory bodies: Direction Générale de l'Aviation Civile (DGAC), the French National Aviation Authority.

Stakeholders can express needs and desires related to the optimization of indoor inspections relying on a cost effective and time saving system. The customer expects the system to provide data which are used to detect the disorders of the building. These defects include cracks more than 1mm of large, water leakage, surface moisture, vegetation growth and corrosion both on building elements and systems. As stated in section II, an operator supervises the system from a ground station while it is performing the inspection to ensure safe and secure operation. Up to two people are required to manage the whole system within its operational environment which can reduce the workload by more than 30% compared to the traditional means.

Requirements are derived from the needs and desires in close interaction with stakeholders. A glossary can be built to define the words precisely and avoid ambiguity in the requirements statements. Glossary terms are capitalized throughout the requirements to show that they have a specific meaning in the context of the statements. An extract of these high-level stakeholder requirements are listed in table I and are classified into functional, structural, and behavioral requirements.

TABLE I
STAKEHOLDERS REQUIREMENTS

ID	Stakeholders requirements
	Functional
Stk.F.Rq.01	The system shall operate inside the Building
Stk.F.Rq.02	The system shall detect the Disorders of Building_Elements
Stk.F.Rq.03	The system shall detect the Disorders of Building_Systems
Stk.F.Rq.04	The system shall evaluate the Technical_Performances of the Building
Stk.F.Rq.05	The system shall provide feedback to the operator
Stk.F.Rq.06	The system shall receive Order from the operator
	Behavioral
Stk.B.Rq.01	The system shall operate within a radius of 100m from the Ground_Station
Stk.B.Rq.02	The system shall work in Building with Multiple_Storeys
Stk.B.Rq.03	The system shall ensure the safety of the operator
Stk.B.Rq.04	The system shall ensure the safety of the resident
Stk.B.Rq.05	The system shall handle abnormal situations
Stk.B.Rq.06	The system shall have an energy autonomy more than 45min
Stk.B.Rq.07	Up to two people shall handle the system
Stk.B.Rq.08	The system shall emit less than 80dB noise
Stk.B.Rq.09	The system should be set up within less than 15min
Stk.B.Rq.10	The energy storage system shall be accessible within less than one minute
	Structural
Stk.S.Rq.01	The system shall include the building information collection system
Stk.S.Rq.02	The system shall include the information storage system
Stk.S.Rq.03	The system shall include the obstacle avoidance system
Stk.S.Rq.04	The system shall include the energy storage system
Stk.S.Rq.05	The system shall include the communication system

These stakeholder requirements will be translated into system requirements that will serve as inputs for the next steps of the development process. For instance, from the Stk.F.Rq.02 'The system shall detect the Disorders of Building_Elements', several system requirements can be derived such as 'The system shall take pictures of the Building_Element', 'The system shall analyze the picture of the Building_Element', and 'The system shall store pictures of the Building_Element'.

C. *Operational analysis*

Operational analysis considers the system within its operational environment. In addition to the involved stakeholders listed in the previous subsection, external systems interacting with the system during its operational life can be identified.

TABLE II
OPERATIONAL MODES

Id	**Operational modes**	**Description**
OM01	Power OFF	The system is powered off
OM02	Power ON	The system is powered on
OM03	Initialization	The system is performing self-tests and calibrations before starting the operation
OM04	Nominal	The system is operated with all its nominal capabilities
OM05	Stand-by	The system is waiting for mission order or for powering off order
OM06	Failure	The system is encountering failure impacting one or more capabilities
OM07	Training	The system is operated with limited capabilities which are sufficient for training purpose

For instance, the system interacts with the building itself which is composed of its elements and systems as stated in section II; the external energy source which provides energy to the system; and the environmental conditions of the operational site which is characterized by the weather, the lighting, the visibility and the wind speed.

One can describe operational concepts of the indoor inspection system such as:

- OC01: Move inside the building. The system accesses and moves inside the building to cover the targeted areas where it interacts with the building environment.
- OC02: Detect disorders of the building elements and systems. The system performs its intended mission consisting in the inspection of the interior of the building.
- OC03: Ensure the security and the safety of the operator and the residents. While performing its mission, the system interacts with the operator and potentially with the residents of the building to be inspected with respect to all the security measures.

From these operational concepts, system use cases can be defined. For instance, from ‘Detect disorders of the building elements and systems’, use cases are: ‘Take picture’, ‘Analyze picture’, ’Identify disorders’, and ‘Store picture’. Operational modes of the indoor inspection system are presented in table II.

D. Functional analysis

The indoor inspection system can be decomposed into relevant high-level functions to meet the previously defined requirements:

- F01: Provide power. The system provides power to all of its components to achieve the mission.
- F02: Manage power. The system manages the power with a twofold objective: to move to and within the building, and to supply power to its internal subsystems.
- F03: Control the dynamics. The system controls its dynamic characteristics, that are its speed and its direction, to allow the movement and to perform the intended mission.
- F04: Communicate with the operator. The system exchanges information with the operator to receive orders and provide him or her with constant feedback.
- F05: Track the localisation of the system. The system is able to track its position within the building to be inspected.
- F06: Collect building information. The system collects a significant amount of information of both building elements and systems.
- F07: Analyze information. The system should process the gathered building information to detect disorders on both elements and systems.
- F08: Store building information. The system stores the gathered building information which will be provided to the operator.
- F09: Adapt to the environmental conditions. The system considers the environmental conditions of the operation site, especially the ability to operate in poorly lit sites and to deal with airstreams.

From these high-level functions, the context diagram in figure 1 depicts a high-level functional architecture of the system. The central rectangle represents the indoor inspection system as a set of functions. It is composed of high-level functions represented by the rectangles with a stereotype *’function’* for clarification, and linked to the indoor inspection system thanks to composition associations (represented by solid lines with solid diamonds on the composite end). These high-level functions can be refined and decomposed into low-level functions to specify the subsystems composing the system.

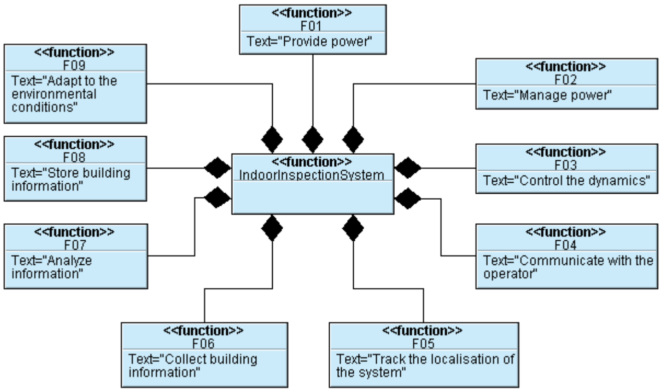

Fig. 1. High-level functional architecture of the indoor inspection system

E. Logical analysis

The high-level functions presented in the previous section can be associated to logical blocks to build a preliminary logical architecture of the indoor inspection system. It is composed of:

- L01: Power Supply. This block stores energy from the external source and provides energy to the whole system.

- L02: Controller. This block has two main objectives: control the dynamics of the system based on the operator input and sensor environmental data, and to manage the others subsystems work together to perform the intended mission.
- L03: Sensor. This block has two main objectives: measure the dynamic characteristics of the system to compare them to the desired states, and to sense the building and its environment to collect the requested building information.
- L04: Actuator. This block converts energy into action which is the motion of the system corresponding to controller input.
- L05: Structure. This block acts as the skeleton of the system. It holds the other blocks composing the whole system.
- L06: Communication. This block is responsible of the exchanges between the system and the operator.
- L07: Data Storage. This block is responsible of storing the gathered building information.
- L08: Ground Station. This block represents the station from where the operator supervises the mobile part while it is collecting the building information.

The preliminary logical architecture of the indoor inspection system is presented in the SysML context diagram in figure 2. The inspection system is represented by the central rectangle to which the logical blocks are linked with composition associations. At this abstraction level, the logical architecture decomposes the system into subsystems represented by each single logical block.

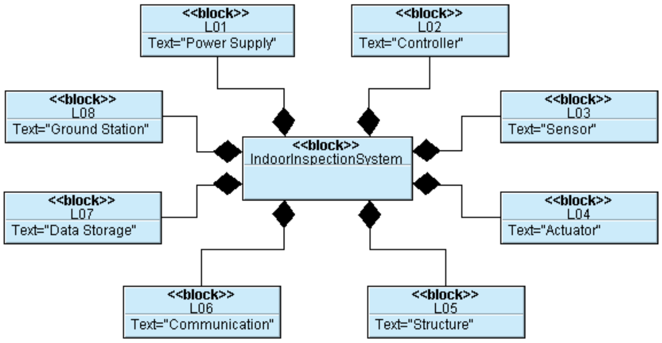

Fig. 2. Preliminary logical architecture of the indoor inspection system

F. Physical analysis

The physical analysis consists in converting the logical architecture into physical architecture which is composed of physical components of the system and their interfaces. To get there, the previous steps of the SE method shall be applied at lower levels of abstraction to detail the subsystems. Further, trade-offs and comparison of different alternative solutions are performed through performance evaluation, sizing, dynamic and structural simulations, and similar.

For instance, imaging sensors such as digital cameras can be selected to get accurate pictures of the building elements to be able to detect the disorders in building elements such as cracks with 1mm of large or surface moisture and corrosion as stated in the requirements. Trade-offs are performed to choose the most convenient reference satisfying the required picture resolution and the weight and power consumption constraints.

Microwave sensors [39] can be selected to detect hidden wiring and pipelines concealed behind walls and flooring to identify anomalies such as damaged insulation and leakages on the electric, HVAC, and plumbing systems of the building. For the propulsion system, electric motor with a given characteristics, such as the torque and the supply voltage, can be selected after having sized the necessary force to move the mobile part.

Given the association of sensors, motors and all the components of the system, the power supply system can be specified. For instance Li-Po battery with a given characteristics including the capacity and the voltage are often used for drones depending on the required power.

Verification & Validation activities check the consistency between each step of the method including the traceability of the requirements throughout the design of the functional, logical and physical architectures.

VI. DISCUSSION AND FUTURE WORK

The previous section applies the systems engineering method at a high level of abstraction, which consists in the system level of an indoor inspection drone whose mission is to detect disorders of an existing building. Further, it can be iteratively applied at lower-levels corresponding to each subsystems of the system, until resulting in a system completely and accurately characterized by all of its physical components satisfying the needs of the customer.

This work shows how to master the complexity for the development of such a drone using a SE approach by addressing the system from various comprehensive and complementary perspectives. Besides, the use of SysML models enhances the understanding of the system.

The case study used in this paper is a part of the 'Indoor Multi-Usages Drone Acquisition' (IMUDA) project whose objective is to prototype an indoor multi-usages drone. The mission of the indoor inspection drone can be extended to other usages, such as the evaluation of the technical performances of the building, that can include structural, architectural, energetic, thermal, hygrometric, and acoustic performances. Further, the drone can be used to create BIM models of the building in the frame of the digitization of the building sector, in order to address and support those various usages, especially the inspection one as stated in section II. Studies are currently underway to refine the mission of the multi-usages drone, and to apply the SE method presented in section IV to master the complexity of the multi-usages drone development. Each step of the method must take the BIM constraints and requirements into account.

VII. CONCLUSIONS

Introducing an indoor inspection drone is an asset to the building industry since it allows time and cost saving operations compared to the conventional means. Designing such a drone is a highly complex task. To cope with that complexity, this paper advocates for using a Systems Engineering approach. This paper compares several SE methods published in the literature according to a set of qualitative criteria to specify a drone.

An iterative seven-step method is proposed to address an indoor inspection drone. The SE method provides comprehensive and complementary views of the system from a global to very specific perspectives which allow mastering the complexity for the inspection drone development. Further, the use of models to run the proposed method enhances the understanding and the design process of the drone throughout the system life cycle, that is applying a Model-Based Systems Engineering approach. The mission of the inspection drone can be extended to several capabilities, especially the creation of digital models of the building to address multiple usages in the frame of the digitization of the building sector.

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