Enhancing Project Management for Cyber-physical Systems Development

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Abstract—In this paper, specific practices are proposed for better managing Cyber-physical Sytems (CPS) projects, called CPS-PMBOK approach. CPS-PMBOK is based on the Project Management Institute's PMBOK body of knowledge. It is focused on the integration, scope, human resource and stakeholder knowledge areas; which were chosen considering a systematic literature review conducted to identify the main CPS challenges.

I. Introduction

CYBER-physical Systems (CPS) refer to computational systems interacting with the physical world [1], [2]. CPS gained remarkable advances in science, such as medical surgery, autonomous vehicles, energy harvesting and smart buildings. A CPS is composed of a computing platform, the physical world, sensors and actuators [1], [2], [3]. CPS merge areas from embedded systems, mechanical engineering, software, among others [3]. CPS development projects tend to be large, complex and groundbreaking, with innovative technologies [1], [2], [4]. A usual feature is multidisciplinarity, which requires good team communication skills as CPS development merges computing and physical concepts. Collaboration among practitioners from different areas (such as software engineering, civil engineering, experimental physics or natural sciences) is needed to accomplish CPS developments [3], [4].

Project management practices aim to enhance the probability of success in a product or service development [5]. Success depends on organization, application area and project goals, and priorities may vary, including: finishing within planned time, meeting agreed scope, reaching satisfactory quality, or finishing in determined budget. Managing a project consists of controlling the development and providing all resources necessary for project execution, and it is a responsibility usually assigned to a project manager. Project management may be useful for many fields in most diverse applications, such as: medicine, civil engineering, software development, advertising campaigns etc. The Project Management Institute gathers best practices in the so-called Project Management Body of Knowledge (PMBOK) [6], which presents tools and techniques for a better management considering experts' knowledge. PMBOK organizes the best practices through five process groups (initiating, planning, executing, monitoring and controlling, and closing) and ten orthogonal knowledge areas (integration, scope, time, cost, quality, human resource, communications, risk, procurement, and stakeholder).

Considering the particularities of CPS projects and the need to manage them to reach their goals according to the success factors established, this paper addresses specific practices for better managing CPS projects. These specific practices are proposed as a PMBOK extension, called CPS-PMBOK. CPS-PMBOK is focused on the integration, scope, human resource and stakeholder knowledge areas. They were chosen considering a systematic literature review conducted to identify the main CPS challenges. Thus, we expect to improve both team communication skills and understanding of the project activities. The proposed practices are based on approaches previously presented in literature as well as the authors' background. We consider that a well-managed CPS project may increase physical world comprehension, modeling and interaction, enhancing the technological advances.

The remainder of this paper presents: related work and research method, the proposed approach, and conclusion.

II. Related Work and Research Method

Although PMBOK is a general-purpose guide, specific application areas, including CPS projects, may benefit from adapted or focused project management practices, which can better drive project activities and prevent common weaknesses [5]. Some authors propose, for example, new techniques for stakeholder management in civil engineering projects and in clinical research environments [7], [8]. Taking organizational structures differences, some works address concerns on stakeholders, scope, human resources, and communications for globally distributed projects [9], [10]. Other authors propose entire revisions of PMBOK processes, knowledge areas or other project management approach adaptations, but in a general way. One example extends the knowledge areas creating the new 'project sustainability management', dealing with reuse of lessons learned and standardization of project management practices within an organization [11].

To propose our PMBOK extension, we used results from a systematic literature review, conducted to link PMBOK's knowledge areas and the CPS development. We used various technical CPS-related terms to embrace as many primary studies as possible, such as: embedded systems, system of systems, sensors network, IoT, and automation and control.

The primary studies obtained were analyzed to find which knowledge areas were subject of study. A relevance score was applied based on the number of times that keywords related

to each area were mentioned. The outcomes are that scope, human resource and stakeholder were the areas with more issues studied. Considering the outcomes of this systematic review, our work proposes project management practices, focused on the CPS context for the scope, human resource and stakeholder knowledge areas. We also propose a generic practice related to the integration area.

These practices were found to manage scope in CPS projects: software and frameworks for requirements analysis, application of international standards, estimates based on use case points and hardware points, specific modeling languages for requirements elicitation and system architecture visualization, requirements review through peer reviewing and Scrum boards, development of design models, meetings with live demonstrations, and requirements lists and model-driven design [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31].

As for the project human resource, these practices were found to CPS projects: use of an expert and multidisciplinary team, statistical estimates and classification of familiarity of team members, training in specific development methods, such as goal- and model-driven and extreme programming, and skill-based human resource management [12], [14], [15], [32], [17], [33], [21], [22], [23], [26], [28], [27].

Finally, considering the project stakeholders, these practices were found as suggestions to address this knowledge area in CPS projects: identification of stakeholders and assignment of tasks following systematic algorithms and norms, assignment of stakeholders within the organization, involvement of stakeholders during the transition between development phases, and workshop meetings and constructive SoS integration model [12], [14], [15], [17], [21], [23], [24], [26], [28], [34].

To propose CPS-PMBOK, we further analyzed all the practices obtained in the primary studies to find practices still not covered by PMBOK and practices already covered but with suggested specializations. The final practices chosen are those most frequently found in the primary studies as well as aligned with the primary insights of the authors of this work.

III. The CPS-PMBOK Approach

CPS-PMBOK is composed of the original set of PMBOK best practices, extending it for CPS projects. The specialization address four PMBOK's areas. For each, one or more practices are proposed: *(a)* integration – characterization model (artifact); *(b)* scope – pre-elaborated requirements lists (technique), review requirements (process), process simulation (technique); *(c)* human resource – specialized team division (technique), cross-training (technique); *(d)* stakeholder – build technical trust (technique), dynamic follow-up strategies (technique).

A. Project Integration Management

The proposed practice 'characterization model' should be used as a brainstorm driver, to equalize the comprehension and familiarization with the system being developed. It should be produced as an output of the develop project chart process, which is part of the initiating process group; and it

should be used as input by all processes that use the project charter also as input, i.e.: plan scope management, collect requirements, define scope, plan schedule management, plan cost management, plan risk management, and plan stakeholder management. During the brainstorming, participants should indicate levels for some characteristics, providing estimates about project size and technical challenges besides to discussions among team members. These characteristics are divided in: *(i)* CPS environment, representing the variables present in the CPS to be developed, such as how much limited tasks are required, communication with known group of devices, interaction with known group of people, and industrial standards or norms should be followed and *(ii)* CPS complexity, based on specific technological areas, such as mechanical structures, network, sensors, actuators, data storage, user interaction, legacy systems integration, and power energy systems.

B. Project Scope Management

In terms of scope, some processes present special challenges for CPS projects due to their highly innovative and dynamic aspects [35], [2], [4], [3]. In addition, the high complexity involved for modeling the physical world and its phenomena is another challenge source. CPS project managers and team should be able to constantly look for new requirements, bringing up changes in scope as soon as possible. As a result of this scenario and needs, two practices are proposed to the scope management, as presented in this section: pre-elaborated requirements lists and review requirements.

1) Pre-elaborated Requirements Lists Technique: to gather requirements, CPM-PMBOK includes a technique called pre-elaborated requirements lists to create reusable assets by gathering common requirements in CPS projects. This technique is proposed to be used within the collect requirements process, which is part of the planning process group.

2) Review Requirements Process: CPS development may lead to unexpected results and dynamic requirements [23]. Since such scope revisions and redefinitions are highly common in CPS projects, one of our specific practices is proposing an additional process to the scope knowledge area – review requirements – as part of the monitoring and controlling process group. Review requirements results in change requests similarly to performed by the control scope process, as described in PMBOK. The difference is that, in CPS-PMBOK, review requirements is a creation-focused process, considering less the already known requirements and revisiting the highest definitions of the project looking for new requirements. In PMBOK, the control scope process focuses on ensuring the accomplishment of the defined scope and, when needed, the appropriate processing of changes is made. In this new process, techniques to collect requirements already described in PMBOK are used, as meetings, surveys and interviews.

3) Process Simulation Technique: this technique is added in support of review requirements. Simulation tools to predict environment or conditions such as mechanical simulation, radiation diagrams and thermal dissipation are useful in review requirements and are part of process simulation. Other tools

to isolate part of the CPS, to validate models or equipment, such as hardware or software in the loop may be used.

C. Project Human Resource Management

Considering multidisciplinarity, human resources can be from different specialization areas, what increases the challenge of managing relationships and technical communication [33]. As a result, two additional techniques are proposed in CPS-PMBOK for human resource management: specialized team division and cross-training.

1) Specialized Team Division Technique: specialized team division is included in CPS-PMBOK to improve the development performance and avoid inappropriate assignment of tasks. The team should be split into subteams taking different application areas or project deliverables. Some works found in literature were used as a basis to propose it, including: the application of team division based on academic profiles, such as electrical engineering, computer engineering and information technology [22], [2]. This technique is proposed to be used within two processes: the plan human resource management process, which is part of the planning process group; and the acquire team process, which is part of the executing process group. We propose an initial suggestion for a specialized team division considering the context of CPS projects and taking into account the proposed characterization model in terms of CPS complexity. According to our suggestion, the sub-teams for a CPS projects could be: *(a)* mechanical design team – responsible for physical structures and mechanical packing; *(b)* hardware design team – responsible for processing platforms, sensors and actuators specification; *(c)* electrical design team – responsible for electrical project and drawings, besides power energy design; *(d)* network design team – responsible for communication protocols and technologies specification; *(e)* information system development team – responsible for software development; *(f)* other specialized teams – power bank development team, human-computer interface team, antenna design team, specific sensors team etc. Other options for specialized team division can be used according to specific project needs, based on the context of the system application. An alternative division is based on deliverables or partial results of the project, assigning a focused team for each logical deliverable part of the developed CPS system. A specialized team division may be used to support organizational or resource breakdown structures.

2) Cross-training Technique: cross-training is a practice briefly depicted in PMBOK, proposed to reduce impact when a team member leaves the project. It consists in allocating more than one resource to a task execution. For CPS projects, we propose that the cross-training should be always used to enable some team members acting as a communication bridge between different sub-teams by allocating a team member from a given area to perform a task of some other area. This technique is proposed to be used within the develop team process, which is part of the planning process group. Considering cross-training, a software engineer may sporadically follow a mechanical engineer's work with the purposed of understanding and even positively contributing with potential ideas and insights emerged from another outlook. Cross-training can be used as a facilitator in the identification and development of multidisciplinary practitioners.

D. Project Stakeholder Management

Project stakeholders in CPS projects are usually highly technical or very close to the system's final users. This occurs mainly in joint projects of research with universities, involving researchers and students. Also in industrial projects aiming to improve production performance, where many stakeholders are production leaders experts in many technologies of the area [4]. Consequently, two additional techniques are proposed in CPS-PMBOK for stakeholder management: build technical trust and dynamic follow-up strategies.

1) Build Technical Trust Technique: CPS projects tend to involve academic researchers or experts to support the development of CPS physical elements. They may represent technical stakeholders who know both the application and engineering areas. PMBOK describes a practice of trust building for stakeholder engagement management, showing that the company, team and the manager have competencies to accomplish project's requirements in time and cost. Accordingly, when involving technical stakeholders in CPS projects is to build technical trust between them and the team. In this context, CPS-PMBOK proposes a specialization of the trust building, adding the technical aspect to this practice. Build technical trust is proposed to be used within the manage stakeholder engagement process, which is part of the executing process group. Build technical trust means to pass technical confidence regarding project accomplishment conditions, considering the team and project manager. Accordingly, the team should get close to the stakeholders, mainly in situations in which the stakeholders are highly technical. For CPS-PMBOK, an internal expert or an external consultant should be put in charge of following up the project management activities allowing more technical stakeholders to be more comfortable with the project progress. This person has the role of translating technical stakeholders concerns. The technical trust may improve stakeholders' satisfaction due to their proximity and understanding of technical issues. Besides that, the developers may feel more comfortable as well, due to the understanding of terms and concerns provided by a expert or consultant.

2) Dynamic Follow-up Strategies Technique: some approaches found to improve communication with CPS projects' stakeholders are: face-to-face meetings to update the project status to stakeholders [23], stakeholders' participation in every last weekly follow-up meeting of development iterations [21], and weekly workshops for system demonstrating – to update stakeholders [24]. Most of these approaches are based on agile methods, which has the communication with stakeholders as one of their most important concerns. To meet the different levels of demand and satisfaction of stakeholders, we propose dynamic follow-up strategies as part of CPS-PMBOK. This technique is proposed to be used within two processes: the manage stakeholder engagement process, which is part of the

executing process group; and the control stakeholder engagement process, which is part of the monitoring and controlling process group. According to different aspects of a given specific CPS project, the project manager should adapt the follow-up strategy aiming to enhance stakeholder engagement and reach their expectations. The following suggested strategies are proposed: *(i)* during the project initiation and planning stages, which involve, for example, discovering of requirements and stakeholders, understanding of highly engaged stakeholders, and understanding of stakeholders' application area – regular face-to-face meetings should be adopted as follow-up strategy; *(ii)* during the project execution and monitoring stages, which involve, for example, resolution of requirements conflicts and alignment between technical demands from stakeholders and project documents – only sporadic participation of stakeholders could be included during planning and technical meetings; and *(iii)* during the closing stage, which involves, resource scarcity, time re-planning and stakeholder staff updating – the stakeholders should be able to follow up on the final results through workshops with live CPS demonstrations.

IV. Conclusion

This work proposed project management practices driven to CPS projects. The approach is based on PMI's PMBOK best practices and focused on integration, scope, human resource and stakeholder. CPS-PMBOK relies on the following requirements for CPS projects: multidisciplinary teams, high level of innovation and unpredictable requirements. Our challenge is to be able to evolve the proposed practices considering two needs that can be seen as antagonistic ones: on the one hand, being specific to the CPS project domain; but, on the other hand, being not too specific in order to allow adjustments as required for specific contexts and organizations.

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