PhD Forum: A Cyber-Physical System Approach To Embedded Visual Servoing

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***Abstract*—Visual servoing, which applies computer vision as a feedback source for control, is becoming a cost effective solution for high performance mechatronic systems. However, the potential of visual servoing systems is limited by the current design methodology, which explores the cyber domain and the physical domain separately. We propose to use a cyber-physical system approach to overcome such limitation.**

I. Challenges of Embedded Visual Servoing

Visual servoing, which applies computer vision as a feedback source for control, has been widely used in robotic applications [1]. In the early days, visual servoing was mostly applied in a look-then-move configuration, in which vision was a feedback source for outer-loop high-level control. Recent advances of high frame rate cameras enable the computer vision as a direct feedback source for motion control. The block diagram of visual servo control is illustrated in Fig 1. Visual feedback could provide higher accuracy than encoder feedbacks, because vision provides position sensing close to the end-effector. However, designing a vision system, especially an embedded vision system, for high frame rate visual servoing is challenging in multiple ways.

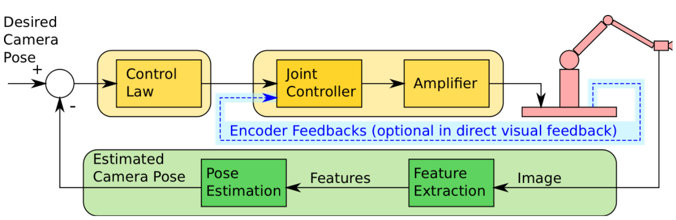

Fig. 1. The block diagram of visual servo control. In a look-then-move configuration, the encoder feedbacks, shown in blue color, are the inner loop feedback sources. In a direct visual feedback configuration, vision can be used as the only feedback source, while the encoder feedbacks are optional.

First, computer vision, control, electronics, mechanics, and possibly other domains, are tightly coupled. Changing the design choices in one of these domains will affect the others. In one of our case studies [2], the authors have already observed the tight coupling of many domains, as shown in Fig 2.

Second, the time predictability of the vision processing is hard to guarantee. To demonstrate such challenge, the reader can refer to an example of a time-predictable histogram on GPU [3]. The time predictability of the vision processing involves the interplay of algorithms, programming models, and computer architecture.

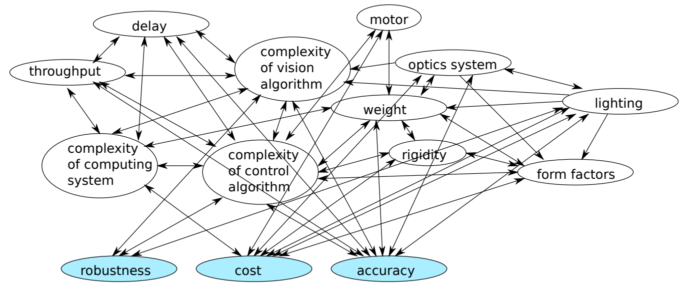

Fig. 2. The coupling of multiple domains in a real-world visual servoing system [2]. Several design targets, as highlighted in blue circles, are affected by many design choices. To keep the figure readable, not all dependencies are illustrated as edges in this figure.

Third, to effectively explore the design space of the visual servoing system, models of multiple domains need to be integrated. However, to the best of our knowledge, the model-based design method has not been applied to visual servoing applications. Integrating the model of computer vision domain with models of other domains remains a research challenge.

II. Cyber-Physical System (CPS) Approach

The current design methodology of visual servoing systems separately explores the design choices of different domains, e.g., control, vision, and computing systems, as illustrated in Fig 3. When the design is separated into different domains, each domain assumes other domains will satisfy certain requirements. For example, the design of control algorithms needs to assume the vision feedback has a certain error and the computing system has a certain delay, which may turn out to be infeasible at the system integration. The current design method usually applies design margins to tolerate these estimation errors to a certain extent. However, this method cannot, at design time, guarantee the integration will meet the overall requirements.

The cyber-physical system approach [4] integrates models of heterogeneous domains to enable cross-domain design space explorations, as shown in Fig 4. To avoid the properties of the model being invalidated at the implementation, the tool-chain will synthesize the design preserving the properties of the model. The CPS approach, if applied successfully, will overcome the challenges mentioned in Section I.

The authors will use two real-world applications to drive the research: visual servoing on repetitive patterns [2] and active vision for visual attention [5]. The first application is

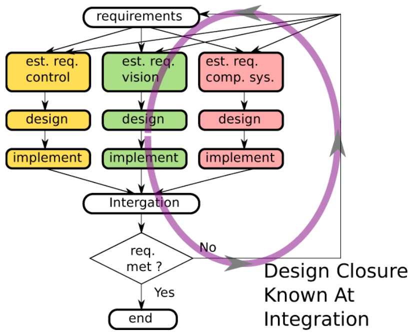

Fig. 3. Current design methodology of embedded visual servoing systems.

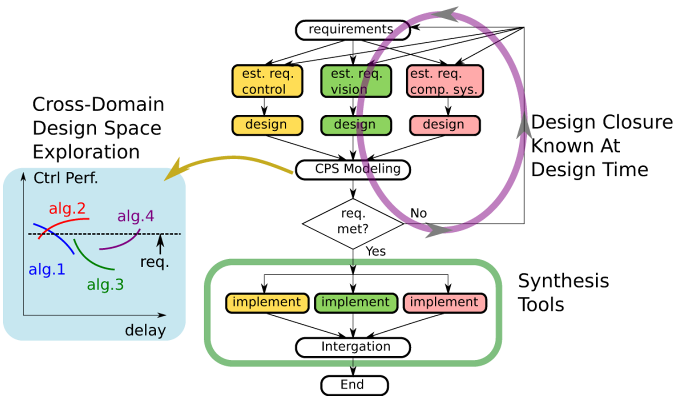

Fig. 4. The CPS design methodology of embedded visual servoing. It enables the cross-domain explorations of algorithmic choices (four algorithms in this figure) and the tuning of each algorithm, e.g., the aggressiveness of model reduction, the stopping criteria of an iterative solver, etc.

under study using the CPS approach. Part of its design space is illustrated in Fig 5. In this figure, limited design choices are modeled, and simple dynamics is assumed, e.g., without friction. Yet it illustrates what a designer can expect, and benefit, from the CPS design methodology.

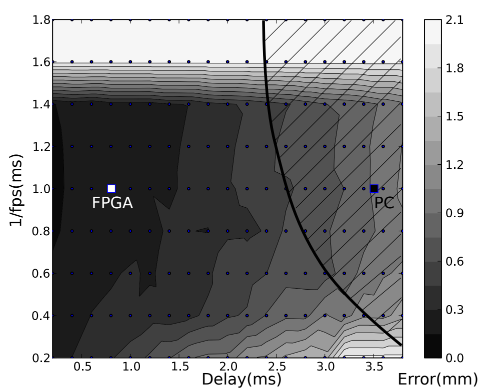

Fig. 5. An example showing the cross-domain design space of a visual servoing application [2]. The control performance, in terms of tracking errors, is simulated at various delays and various frame rates, plotted using the reverse of frames-per-second (1/fps), of the visual servoing system. Two design points, implemented on an FPGA and on a PC respectively, are annotated in the figure. The hatching area is the *speculated* design space of a PC based solution, which is to be verified in the future work.

III. Possible Fallacies

The authors frequently encountered questions about the proposal. Several fallacies are worth mentioning.

1) *Fallacy*: The proposal includes ”yet another case study of CPS”, not leading to fundamental breakthroughs.
   Disclaim: The dynamism and parallelism of vision applications post new challenges not present in previous case studies of CPS. These new challenges will drive the developments of new CPS methodologies.
2) *Fallacy*: The CPS approach is a naive combination of basic knowledges in each domain.
   Disclaim: The authors believe cross-domain integrations will lead to new design methodologies in each domain.
3) *Fallacy*: It takes ten PhDs to complete this proposal.
   Disclaim: The core task, cross-domain modeling, is not beyond the capability of a PhD. Other tasks will be supported by a team of experts in multiple domains.

Due to the page limit, other possible fallacies are to be discussed at the phd forum.

IV. Risks And Backup Plans

The authors are aware of the risks that would arise at the carry out of the project. The risks that we are most likely to run into are listed here.

1) *Risk*: Developing a framework to model heterogeneous domains requires too much engineering efforts.
   Backup: We can extend existing frameworks, e.g., Ptolemy [6], or develop a minimum framework just to support the modeling of our applications.
2) *Risk*: Not all components of CPS are time-predictable.
   Backup: As a research project, we can afford to design algorithms, hardware, and software from the ground up to be time-predictable. This approach is proven feasible in our previous case study [2].
3) *Risk*: Part of the design space cannot be modeled.
   Backup: If only a small part cannot be modeled, it can be explored by simulations or experiments. Otherwise, heuristics and approximated models, compromising the scope and the accuracy respectively, can be used.

Due to the page limit, other risks and backup plans are to be discussed at the phd forum.

References

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