Exploring future directions of control

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Exploring future directions of Control

Tai C. Yang, Argyrios C. Zolotas, Timothy J. Wren, Hong N. Yu

Abstract — **Control system research is entering a new era, which may be considered a milestone in the history of Systems and Control. The traditional framework of a control system structure – i.e. plant, sensor, actuator and a controller – presents a number of limitations to some current research, i.e. (a) System to be controlled comprise network of subsystems; (b) Control task is achieved by a network of distributed local controllers (agents); (c) New research topics on control of networked behaviour, including consensus, formation and synchronisation, are clearly beyond the scope of the traditional "one controller" framework. It is worth noting that with these new trends some new concepts are emerging, e.g. consensusability, formationability, computability. The intended contributions of this paper are: (1) A new framework of control research represented by a new block diagram and its mathematical treatment. It is pointed out that, many current different studies can be considered as some special cases under this general framework; (2) a brief overview of various research fitting the proposed framework and some open questions. This paper is largely motivated by past, current and future applications of power system control, and is based on a recent invited presentation, of the first author, at a special workshop on "Bridging the Gap – Control Theory and Control Engineering Practice".**

I. Introduction

To reflect some current research in control and beyond, a new block diagram [1] (Figure 1) accompanied by a mathematical treatment in Section II, is proposed. This can be considered as a natural extension of some concepts that appear in existing control literature – i.e.see [2-6]. To the best knowledge of the authors, the proposed framework can be considered as the first attempt to encapsulate the characteristics in the design of emerging control research as listed in the abstract above. Figure 1 and Figure 2, present the block diagram of the proposed control scheme and of a conventional feedback control setup respectively.. . In this paper, various aspects of the proposed Control Network of Subsystems (CNS) framework are explored in Section 2, and conclusions presented in Section 3.

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II. Control Network of Subsystems (CNS)

A. Modelling of CNS

We follow the same notation and definitions as the ones used in [7]. Consider a distributed CNS containing N subsystems − also referred to as agents − these N agents are coupled and each agent receives information from neighboring agents. The coupling and information flow in CNS can be described by a coupling graph and a communication graph, which are defined as follows.

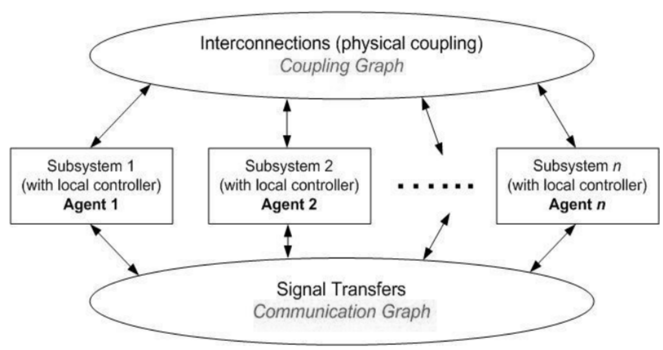

Figure 1: Control a network of subsystems

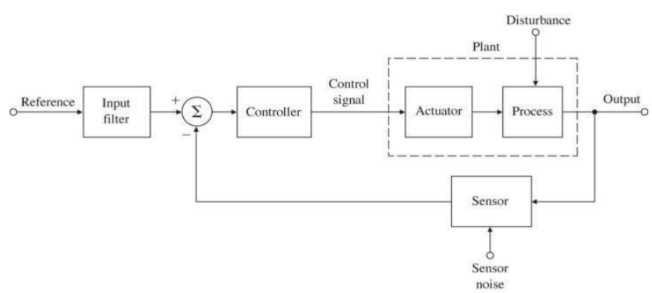

Figure 2: A typical feedback control system (an observer can be included in the controller)

Definition 1: A graph $G_{cp} = (N, \varepsilon_{cp})$ is called the coupling graph of a CNS, where each node $i \in N$ represents an agent in the CNS. The ordered pair (edge) , (*i, j*), is in ε_{cp} if agent *j* is directly driven by agent *i*.

Definition 2: A graph $G_{cm} = (N, \varepsilon_{cm})$ is called the communication graph of a CNS, where each node $i \in N$ represents an agent in the CNS. The ordered pair (edge) , (*i, j*), is in ε_{cm} if agent *j* can receive broadcasts from agent *i*.

For notational convenience, we let

- $Z_i = \{j \in N | (j,i) \in \varepsilon_{cm}\}$ denote the set of agents that agent i can get information from,
- $D_i = \{j \in N | (j,i) \in \varepsilon_{cp}\}$ denote the set of agents that directly drive agent i, and
- $S_i = \{j \in N | (i,j) \in \varepsilon_{cp}\}$ denote the set of agents who are directly driven by agent i.

Let $\overline{\Sigma}_i = \Sigma_i \bigcup \{i\}$ for any set $\Sigma_i \in \{Z_i, D_i, S_i\}$. For any set $\Sigma \subseteq N$, $|\Sigma|$ denotes the number of the elements in Σ.

The state equation of agent i is

$$\dot{x}_i(t) = f_i(x_{\overline{D}_i}(t), u_i(t), w_i(t)) \quad (1)$$

$$u_i(t) = g_i(x_{\overline{Z}_i}(t)) \quad (2)$$

where $x_i : \mathrm{R} \to \mathrm{R}^n$ is the state trajectory of agent i, $u_i : \mathrm{R} \to \mathrm{R}^m$ is a control input, $w_i : \mathrm{R} \to \mathrm{R}^l$ is an exogenous disturbance in L_p space, g_i is the feedback strategy of agent i satisfying $g_i(0) = 0$, f_i :is a locally Lipschitz function satisfying $f_i(0,0,0) = 0$, and $x_{\overline{D}_i} = \{x_j\}_{j \in \overline{D}_i}$, $x_{\overline{Z}_i} = \{x_j\}_{j \in \overline{Z}_i}$.

The assumption followed is that agent i can only detect its own state, x_i, and receive the broadcast states of its neighbors in Z_i. As shown in Eq. (2), $x_{\overline{Z}_i}$ is used for feedback control. For physical systems, for example due to Newton's third law and Kirchhoff's current law, $D_i = S_i$, i.e. the coupling graph is undirected. Therefore, within the scope of this paper we assume $D_i = S_i$ and only consider D_i.

B. Consensus and Cooperation: A Special cases of CNS

Recently, consensus and cooperation in networked multi-agent systems has attracted a great deal of research interests. According to [9], many seemingly different problems that involve interconnection of dynamic systems in various areas of science and engineering happen to be closely related to consensus problems for multi-agent systems. These include:

- Synchronization of Coupled Oscillators
- Flocking Theory
- Fast Consensus in Small-Worlds
- Rendezvous in Space
- Distributed Sensor Fusion in Sensor Networks
- Distributed Formation Control

Overall, all above consensus problem can be modelled as:

$$\dot{x}_i(t) = f_i(x_i(t), u_i(t), w_i(t)) \quad (1\text{-C})$$

$$u_i(t) = g_i(x_{\overline{Z}_i}(t)) \quad (2)$$

Notice that (1-C) is almost the same as (1) except the first term on the right: there is no direct physical coupling between agents. For example, in a coordinated movement of a group of robots, one robot's change in position/speed will not directly affect another robot's dynamics (This would happen, for example, if there were a spring connecting two adjacent robots). Consensus control which uses agents' positions/velocities as inputs is reflected in Eq. (2). Under the proposed new framework, consensus control is to change reference signals for subsystems. How a subsystem responses to its reference signal change is totally dependent on its own dynamics. For example, in a military application different combat unit by air, sea and land are targeted to arrive at a common location at the same time. They adjust their reference signals according to a designed protocol during travelling. The units' actual movements follow the changing references, with the updated positions/velocities fedback to the consensus control. Therefore, from this viewpoint: (1) naturally, dynamics of all agents are assumed heterogeneous and can be very different; and (2) a block diagram of Figure 3 can be used to cover all consensus problems, which is a special case of Figure 1.

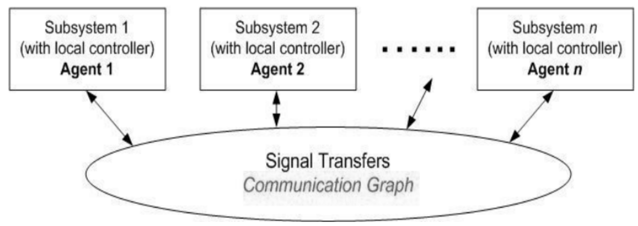

Figure 3. Consensus problem under current study: subsystems do not have physical coupling

Moreover, a seemingly different control research area: decentralised control for large-scale systems can also be consider as a special case of CNS. A general diagram for decentralised control can be obtained by keeping the top part but removing the bottom part of Figure 1 – has physical couplings but no communication between subsystems. In terms of modelling equations:

$$\dot{x}_i(t) = f_i(x_{\overline{D}_i}(t), u_i(t), w_i(t)) \quad (1)$$

$$u_i(t) = g_i(x_i(t)) \quad (2\text{-D})$$

The issue of decentralised control to proposed Scalable Control for Physically-Coupled Subsystems (SCPCS) is the discussed in subsections II.E and II.F

C. Consensus problem: suggested research

Figure 4 is intended to give an overview illustration of the research on the consensus problem. Depended on how the subsystem is modelled and the characteristics of communication between subsystems, each research has its own unique feature. For example in [10] it studies subsystems comprising first-order and second-order integrator agents, and the communication graph is fixed and switching.

One direction worth noting is that in most current studies, the motion of agents has no restriction in a linear vector space. However, in many applications agents are often constrained to evolve on a nonlinear manifold, such as oscillators on a circle S1, satellite attitudes on SO(3) and vehicles in SE(2) or SE(3) [11, 12]. This is an area of consensus on nonlinear spaces, and the interested reader is referred to paper [13] which provides good background and a brief survey.

It appears that so far for the consensus problem, all are seeking analytical solutions. If optimisation is also considered − for example minimising the total energy consumption while reaching a common location, or -in a military application- to reach a common location in a shortest possible time − to solve these optimal consensus problems, one may have to resolve numerical solutions.

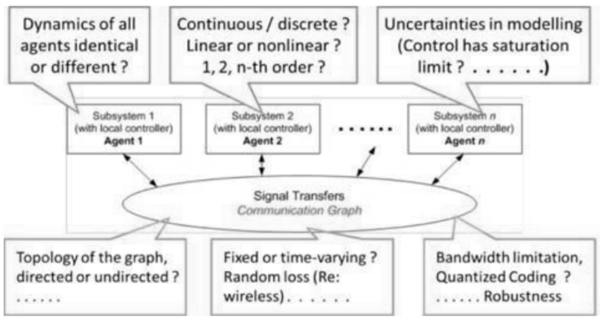

Figure 4. Consensus problem: dynamics of subsystems and topology of communication graph

Consensus problem has wide applications, while received a major attention of from researchers in many fields such as system control theory, applied mathematics, statistical physics, biology, communication, computer science. However, in the case of power systems engineering, one notice research [14] to make a group of photovoltaic generators in a power distribution network to operate at certain (or the same) ratio of available power. In fact, for traditional economic dispatch among the available power generation units is to seek a common incremental cost point, known as "equal lambda criterion" [15]. These two power engineering consensus problems can be represented by Figure 3. The consensus problem under current studyconsiders subsystems that do not have physical coupling".

Furthermore, traditional nonlinear power flow calculation can be considered as a consensus problem in terms of formation – each bus is an agent and the voltages of all buses to reach a set of relative "positions" so that all power mismatches become zero [15]. Power system transient stability can also be considered as a formation problem for machine angles where each machine is an agent. However, in these two problems there are physical couplings between agents (subsystems) as shown in Figure 1. We note the three consensus problems outlined here: *economic despatch*, *power flow* and *transient stability* have not been investigated yet.

In summary, current research on consensus has two main limitations: (i) its application to power systems has not been fully explored, (ii) there is no work on consensus where subsystems are physically interconnected, i.e, the consensus problem for the system represented by Figure 1.

D. Decentralised control and beyond: a brief review.

In the early development of control, the main feature was a centralised controller structure. In the 1970s and 1980s, control applications were extended to large-scale systems, which stimulated extensive study of decentralised control. A large-scale system "plant" is typically decomposed into a number of interconnected sub-systems. In terms of an electrical power system, a generation plant located in place *A* can be considered as a subsystem and another generation plant located in place *B* is another subsystem. All generation plants (subsystems) are connected via transmission lines. Such physical connections can be modelled by a (weighted) coupling graph shown at the top part of Figure 1. The dynamics and control of a subsystem can affect the dynamics of the whole system. Under a decentralised control scheme, a number of local controllers are connected to each distributed sub-system, and there is no measurement and control signal transfer between different subsystems, i.e., there is no "Communication Graph" as shown at the bottom part of Figure 1. This is also reflected in Eq. (2-D) as a special case of Eq. (2).

In terms of conventional matrix modelling, the above case, has a full matrix under centralised control, and a block-diagonal matrix under decentralised control. When modern communication techniques were not available, decentralised control was the only solution in some applications. However, apart from the obvious performance limitation due to that the control matrix is limited to being block-diagonal, it has already been established that, given a plant and a decentralised control structure, there may not exist any decentralised stabilising controllers (not to mention robust decentralised stabilising controllers). Indeed, Wang and Davison [16] first introduced the notion of decentralised fixed modes associated with a controller structure. A stabilising controller exists if these fixed modes are stable. Amongst the most important work in this area is that of Siljak [17], which developed state-space and graph-theoretic methods to address the problems of decentralised stabilisability, decentralised controllability, fixed-mode characterisation, and decentralised controller design.

There was an implicit assumption, in many early stage theoretical studies , that if any fixed modes were unstable a centralised controller would be required. The term *centralised control* refers to a situation in which all measurements are collected and sent to a central unit for processing, and the resultant control signals are then fedback to all plants. Without modern network technology, the complexity of centralised controllers often makes the implementation of such a control strategy impossible. To solve the problem where decentralised control cannot provide the required performance and to avoid the complexity associated with the traditional centralised control, first a quasi-decentralised control strategy was proposed [18]. The term *quasi-decentralised* control refers to a situation in which most signals used for control are collected and processed locally — although some signals still need to be transferred between local plants and/or controllers, the total number of such signals is kept to a minimum. This was to reflect the fact that in the early 1990s, remote communication for on-line control was possible but expensive. In terms of the feedback control matrix, under quasi-decentralised control, it is an almost block-diagonal matrix, with a few non-zero elements in the off-diagonal. This is a step forward from decentralised control scheme and the "block diagonal" control matrix. Among many possible applications, quasi-decentralised control is particularly attractive for power system control, see [19, 20].

Networked control, where signals are transferred by a communication network, can be considered to provide a practical means of centralised control for large geographically distributed systems. It has completely removed information structure constraints, and opens up the possibility of a "full" feedback control matrix. However, as discussed before, a centralised control scheme implemented by a networked control system with associated complexity and various other issues are also not preferable [21]. Quasi-decentralised control systems, in which there is some limited communication between subsystems, provide a practical solution to the dilemma discussed. The key questions in Quasi-decentralised control are: *How to choose measurements from other subsystems as additional input signals to the local controller and how to design such a local controller for each subsystem.*

To address the same key questions, in recent years researchers have made some significant contributions in "Decentralized systems with design constraints" [22] and "Structurally constrained controllers" [23] and other related topics [4, 5, 7]. These terms are alternative to the term "Quasi-decentralised control" and all these together can be considered as "distributed control" in general. Recent books, i.e. [22] and [23] cover most research published in recent control journals on the subject, for example [23] covers the topic of "Decentralized Implementation of Centralized Controllers" published in 2012 IEEE-AC [21]. For a comprehensive overview of decentralised control and beyond, the interested reader is referred to [22] and [23] and references within.

E. Proposed new direction: scalable control

In the last section, II D, the number of subsystems and their physical connections are fixed. In the resent study on future power systems, it is proposed to have an "Energy Internet" [24, 25]: an architecture that is suitable for plug-and-play of distributed renewable energy generation and distributed energy storage plants, etc. The vision of "Energy Internet" is analogous to that adopted by the computer industry in the 1980s and 1990s. From the control system point of view, a network of *N* interconnected subsystems need to be easily expanded to *N+1* subsystems while maintain at least its stability. Currently under the framework of large-scale system control, when a new subsystem is added to existing *N* interconnected subsystems − for all design methods we are aware of − one need to re-design the controllers for all *N+1* subsystems, i.e., this is treated as a new large-scale system design problem. This traditional approach can cause major difficulties in applications. For example, for a benchmark of IEEE 118-bus system [26], there are 54 subsystems. The proposed new approach is *scalable control* (see *Definition 3*). This is largely motivated by applications in power systems.

The power systems that exist today were largely conceived and built first in the 1920s and 1930s and then, with grids at higher voltages and over longer distances, to accommodate economies of scale in bulk generation of power and improved reliability of supply in the 1960s. Many of the assets have now reached − or gone beyond − their planned economic lives [27]. However, as well as a very large program of renewal, industry needs to find ways of accommodating renewable generation that is highly variable and uncertain in its output. While these factors together both provide an opportunity but also, arguably, a necessity for "smarter" operation of power systems. The vision by power system engineers is a fundamental change of power system structure: from traditional hierarchical Generation-Transmission-Distribution (GTD) to many (smart) microgrids connecting to a (smart) energy highway network where overall there is a mixture of DC and AC transmission/distribution systems [25]. For consistency we refer to thethe new structure as *Smart Grid* (SG) [28]. The traditional study on decentralised control and large-scale system control is closely linked with applications in power systems under a traditional GTD structure. Nevertheless, the proposed Control Network of Subsystems (CNS) is largely motivated by control problems associated with the forthcoming SG structure in future power systems.

In the framework of large-scale system control, a typical model is [21-23]:

$$\dot{x}(t) = Ax(t) + \sum_{i=1}^{\upsilon} B_i u_i(t)$$
$$y_i(t) = C_j x(t), \quad \forall_j \in \upsilon := \{1,2,\cdots,\upsilon\},$$

where $x(t) \in \mathrm{R}^n$ represents the state of the system S, and $u_j(t) \in \mathrm{R}^{m_j}$, and $y_j(t) \in \mathrm{R}^{r_j}$ are the input and output of the subsystem S_j, respectively.

Comparing the above modelling setup with the model presented in Eqs. (1-2), illustrates that the former is not suitable to study under CNS: (1) The physical connections between subsystems are embedded in the overall state-space matrix *A* and these connections are fixed; (2) The topic of decomposition, including overlapping decomposition, under large-scale system control is not valid under CNS. The results based on decomposition of large-scale systems are not valid under CNS; and (3) Scalable control cannot be studied under this framework.

To introduce the definition of *scalable control*, refer to (1) and (2) as given before:

$$\dot{x}_i(t) = f_i(x_{\overline{D}_i}(t), u_i(t), w_i(t)) \quad (1)$$
$$u_i(t) = g_i(x_{\overline{Z}_i}(t)) \quad (2)$$

Definition 3: If a new subsystem plant, indexed *N+1*, is added to the *N* subsystems of (1-2). Its connections to the existing system can be represented by a set D_{N+1}. If the same control objective, typically stability as appropriated defined, can be achieved by adding an appropriately designed (*N+1*)-th controller defined by (2), and changing those controllers whose indices are in the set of D_{N+1} without a need to change any other controllers, then this is called a scalable control.

Current consensus controls are classified as *scalable control*. When a new agent joints, the protocol does not change. Those agents which are not the neighbours of the new agent do not need to make any change to maintain the convergence of the consensus. In addition, scalable control is already achieved for expansion of communication networks. Therefore, the definition of scalable control above is specifically for Scalable Control for Physically-Coupled Subsystems (SCPCS), where D is not empty.

Similar to that the vector Lyapunov function is the basis for decentralised control of large scale systems, a special form of Lyapunov function – scalable Lyapunov function – is yet to be developed to support SCPCS. The definition of scalable control, with minor changes, is also applicable to the case when a subsystem is removed from the existing network of N subsystems. Furthermore, the "scalable stability" associated with scalable control can be extended to "split-and-connect stability of networks of subsystems". A network of subsystems is "cut in the middle" and splits into N_1 and N_2 subsystems, where the two networks of subsystems are disconnected between them and $N = N_1 + N_2$. When it splits, each network of subsystems should be stable. On the other hand, when two networks of subsystems are connected to a system, this combined $N = N_1 + N_2$ system should be stable. This is the stability issue associated with the new smart grid power system structure, i.e. a few micro grids can be connected together and split as required, or connect/disconnect to a super grid. In fact, in traditional power system transient stability, one or a few generation plants need to be disconnected and reconnected as required and the system stability need to be maintained.

F. *Scalable Control for Physically-Coupled Subsystems*

SCPCS is a very broad topic. Its applications include power grid, social systems, distribution systems, smart buildings etc. Our initial study is limited to a special class of interconnected subsystems:

$$x_i = [x_{Li} \quad x_{li}]^T, \quad x_i \in R^{n_i}, x_{Li} \in R^{n_i - 1}, x_{li} \in R^1 \qquad (3)$$

$$\dot{x}_{Li} = A_{Li} x_{Li} + a_{li} x_{li} \qquad (4)$$

$$\dot{x}_{li} = f_{ii}(x_i) + \sum_{j \in D_i} f_{ji}(x_j, x_i) + u_i + w_i \qquad (5)$$

$$u_i(t) = g_i(x_{\bar{Z}_i}(t)) \qquad (6)$$

$$Z_i = D_i \qquad (7)$$

An example: scalable control for N-inverted pendulums coupled by N-1 springs (Figure 5), has been used to demonstrate a SCPCS design [29].

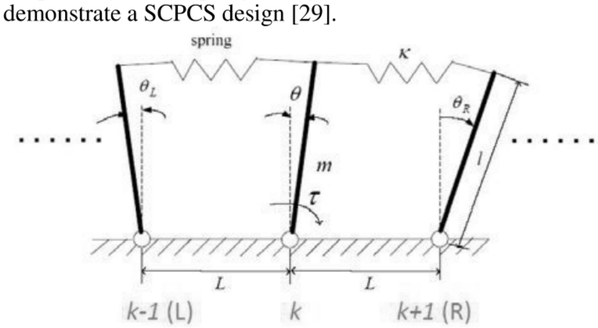

Figure 5: N-inverted pendulums coupled by N-1 springs

For this simple network of subsystems, each pendulum is considered as a subsystem and its couplings to other subsystems are by two springs at its left and right. Coupling graph is a simple one and the communication graph is identical to the coupling graph $Z_i = D_i$. The purpose of the control is stability − more precisely it is finite gain L_p stable from disturbance to pendulum angles, this and the detailed modelling and controller design will be presented in another paper [29].

The system of Figure 5 is a major extension of an example of two inverted pendulums coupled by a spring which is widely used for the study of decentralised control in large-scale systems [17]. The detailed values for the constants and the expressions for the variables of this example are given in [29]. For simplicity and without losing generality, in our demonstration all pendulums and springs are identical. However, parameters, matrices and functions in Eq. (3-5): n_i, A_{Li}, a_{li}, f_{ii}, f_{ij} and g_i can be different for different i. D_i can also be a different structure. Without losing generality, in the appendix, we give a set of equations for two pendulums having different mass and length.

For this example, all D_i has the same structure of connecting to left and right, but in general it can be based on any coupling graph, for example, a graph of Figure 6 to represent an array of 8 inverted pendulums coupled by 11 different springs.

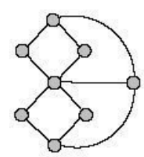

Figure 6: A general undirected graph.

Our scalable control for N-inverted pendulums coupled by N-1 springs is demonstrated by Matlab/Simulink simulations and all files can be downloaded from http://www.sussex.ac.uk/Users/taiyang/ScalableControl.zip. The interested readers can test the system stability by applying different disturbance signals. In this demonstration the system model is constructed by scalable expansion as defined in *definition 3*. The model also includes the dynamics of random time delay and noise in the signal transfer [29].

III. CONCLUSION

A new framework, i.e. Control Network of Subsystems, was proposed. The work presented, illustratesthat current studies on consensus and decentralized control can be considered as two special cases of the proposed scheme. Suggestions on future research, relating to consensus and decentralised control, are also presented. The proposed framework considers: (1) subsystems having physical couplings – which can be represent by a coupling graph − and (2) distributed control not only using local information from its own subsystem but also using information from other subsystems – which can be represent by a communication graph. The proposed framework does not currently consider explicitly the situation of wireless control networks [8] (where instead of distributed local controllers, each node in the communication network is a unit which not only transfers information but also as a computational unit for the overall control).

IV. APPENDIX

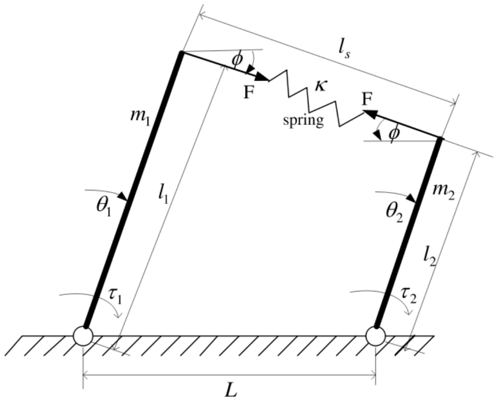

Figure 7: Two pendulums coupled by a spring

$$[m_1(l_1)^2/3]\ddot{\theta}_1 = \tau_1 + m_1 g(l_1/2)\sin\theta_1 + l_1 F\cos(\theta_1 - \phi)$$

$$[m_2(l_2)^2/3]\ddot{\theta}_2 = \tau_2 + m_2 g(l_2/2)\sin\theta_2 - l_2 F\cos(\theta_2 - \phi)$$

where

$$F = \kappa\,(l_s - [L^2 + (l_1 - l_2)^2]^{1/2})$$

$$l_s = [(L + l_2\sin\theta_2 - l_1\sin\theta_1)^2 + (l_2\cos\theta_2 - l_1\cos\theta_1)^2]^{1/2}$$

$$\phi = \tan^{-1}\frac{l_1\cos\theta_1 - l_2\cos\theta_2}{L + l_2\sin\theta_2 - l_1\sin\theta_1}$$

Notice that there is a modeling error in [17] and other related literature. The momentum of the inertia of a pendulum about its pivot point J is $m(l)^2/3$, but in [17] and other related literature this was given as $ml/2$ by mistake.

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