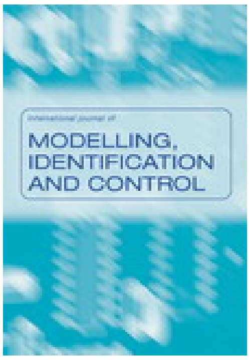

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Four generations of control theory development

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Abstract: In our control community, in particular in our teaching, we often use the terms 'classical control theory' and 'modern control theory'. History moves forward. The word 'modern' here is not appropriate. Today's modern is future's classical. Nevertheless, behind the ambiguous words there are meaningful terms: 'transfer function based' for classical control, and 'state-space based' for modern control. Looking back and forward, and to give an overall overview, this short article presents an opinion that control system study up to date can be divided into four generations; namely: 1) transfer function based; 2) state-space based; 3) networked control systems; 4) control in the new AI era.

Keywords: control theory development; four generations; control in the new AI era.

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Biographical notes: Tai Yang has ten-year industrial experience. His long R+D career covers a wide range of engineering topics. As a distinguished innovator, he was invited to attend a Parliamentary Reception at the House of the Lords, Westminster. He was a member of a special renewable energy mission to visit Israel. He is also a lifetime learner. Over the years, he has been awarded 20+ professional certificates issued jointly by the world-leading institutes and the Coursera online learning platform. His current research interest includes physics-based lithium-ion battery modelling and control.

In our control community, in particular in our teaching, we often use the terms 'classical control theory' and 'modern control theory'. History moves forward. The word 'modern' here is not appropriate. Today's modern is future's classical. Nevertheless, behind the ambiguous words there are meaningful terms: 'transfer function based' for classical control, and 'state-space based' for modern control. Therefore, we call 1st generation of control theory 'transfer function based', and the 2nd generation 'state-space based'. Many overviews of control have been published in journals and conferences. Among all those we have seen, we believe that reference (Astrom and Kumar, 2014) – a 41 page *Automatica* paper – gives an excellent review. From real-word challenges to technology advance, to control theory development, to applications, it gives a good comprehensive survey of the 1st and 2nd generation feedback control development, covering a long period of time and a wide range of disciplines.

Around the beginning of this century, control system research was entering a new era. Traditional framework of a control system structure – plant, sensor, actuator and a controller, see Figure 1 − is no longer applicable to some new research:

a System to be controlled is a network of subsystems, see Figure 2 where the system of Figure 1 is only a subsystem in a networked control system (NCSs).

b Many control tasks are 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 1st and 2nd generation framework, where the control task is often stated as:'…… to design a controller, …… so that the system is stable/robust/optimal'.

With these new trends some new concepts are emerging, for example consensusability, formationability, computability, etc. Third generation of control theory is motivated by NCSs, hence the name. More importantly, two fundamental concepts – stability and controllability – in the 3rd generation of control theory are much different from the 2nd generation.

Figure 1 A typical 1st and 2nd generation feedback control system, the modelling and design tools can be transfer function based and/or state-space based (see online version for colours)

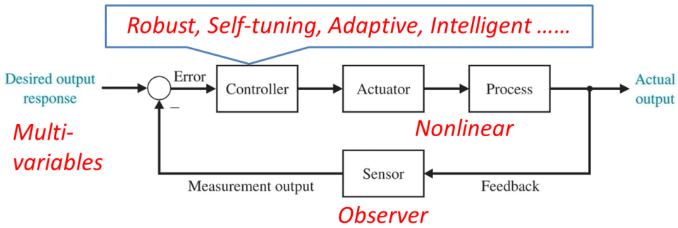
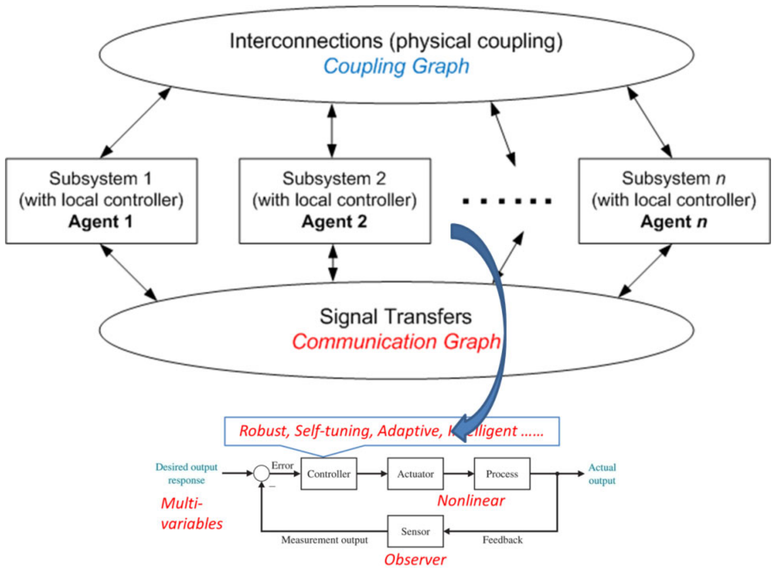
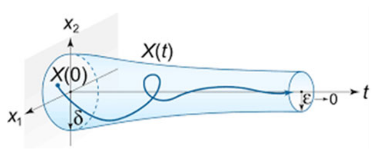


Figure 2 Control a network of subsystems, i.e., 3rd generation feedback control system (see online version for colours)



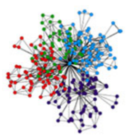
For the stability, Figure 3 is a typical representation of the stability in the 2nd generation of control theory, where 'for any initial condition …… converge to the origin of the state space'. On the other hand, Figure 4 is a typical representation of the stability in the 3rd generation of control theory, where in the case of formation, instead of $x(t) \to 0$, it is $\|x_i(t) - x_j(t)\| \to c$, where c is a constant and in the case of consensus, again instead of $x(t) \to 0$, it is $x_i(t) = x_j(t) \to f(\mathbf{x}(0))$. It will converge to a, normally non-zero, value which depends on the initial condition.

Figure 3 A typical representation of the stability in the 2nd generation of control theory (see online version for colours)



$$\forall x(0) \quad t \to \infty \quad x(t) \to 0$$

Figure 4 A typical representation of the stability in the 3rd generation of control theory (see online version for colours)



$$\forall_{i,j} \quad t \to \infty \quad \|x_i(t) - x_j(t)\| \to c \qquad \text{Formation}$$
$$t \to \infty \quad x_i(t) = x_j(t) \to f(\mathbf{x}(0)) \qquad \text{Consensus}$$

For the controllability, we do a basic overview as follows. Within the framework of the 2nd generation, it is from A and B matrixes to determine if a system are controllable. Under the NCS framework, it first addresses the *structural controllability*: i.e., quoted from Liu et al. (2011): "to determine the *minimum number D* of controllers required to ……". Then how to choose D, among all $N >> D$, notes where control actions are to be applied to make an NCS fully controllable. Following the pioneering work of Liu et al. (2011), there is a lot of interesting and active research. For example, see '2016 Outstanding Paper Award', titled: 'Controllability metrics, limitations and algorithms for complex networks' (Pasqualetti et al., 2014); a paper addressing controllability from the energy point of view, titled: 'Physical controllability of complex networks' (Wang et al., 2017) and two recent 2021 papers, titled 'On the observability and controllability of large-scale IoT networks: reducing number of unmatched nodes via link addition' (Doostmohammadian and Rabiee, 2021) and 'key nodes selection in controlling complex networks via convex optimisation' (Ding et al., 2021) respectively.

Morden artificial intelligence (AI) is a thriving technology for many applications in various areas (Azar and Vaidyanathan, 2022; Nadda and Swarup, 2022; Nasr et al., 2022). Its impact on control is still not fully explored yet. Up to the 3rd generation of feedback control system design, 'desired output response' – as shown in the left of Figure 1 – is always given before controller design. Now this is changing. For example, for autonomous driving in very complicated environments, AI first works out the desired travelling trajectory as a reference signal, then the rest of control system to follow. Due to this and other AI potential for control, we think that control theory and application has begun its 4th generation journey: 'control in the new AI era'.

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