# Closed-Loop Identification to Unravel the Way the Human Nervous System Controls Bodily Functions

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**Abstract.** The central nervous system controls body functions and initiates actions through an integrated system of multiple feedback loops. System identification can be a valuable tool to assess the system dynamics. The challenge is to assess the functioning of an intact feedback system in vivo, where cause and effect are intermingled. In this paper we show the errors which can occur when estimating system dynamics using standard (open-loop) system identification algorithms in the presence of feedback loops. Furthermore, we show how these issues can be addressed by using closed-loop algorithms. A closed-loop system identification approach is essential to assess the separate feedback loops of the central nervous system in an intact functional system.

## 1 Introduction

The central nervous system (CNS) is the initiating and regulating organ in the human body. The CNS controls body functions and initiates actions through an integrated system of multiple feedback loops. Many feedback loops are present, with sensors and actuators, to control the behavior in many organs, e.g. reflexes in human motion control and the baroreflex to regulate blood pressure. The combination of controller, actuator, plant (i.e. the system to be controlled) and sensor form a closed-loop system, see Fig. 1. The dynamic behavior of a closed-loop system can be quite unpredictable from the dynamic behavior of the individual components. System identification is an essential tool to estimate the dynamics of these individual components.

For example, human movement is generated through an orchestrated interaction of muscles, skeleton, sensory systems and the brain. This interaction makes it difficult to understand human motion control from just observations. Increased joint stiffness in stroke patients can be caused by increased stiffness of muscle tissue or by increased muscle activation through feedback from stretch sensors. In case of the former, surgical

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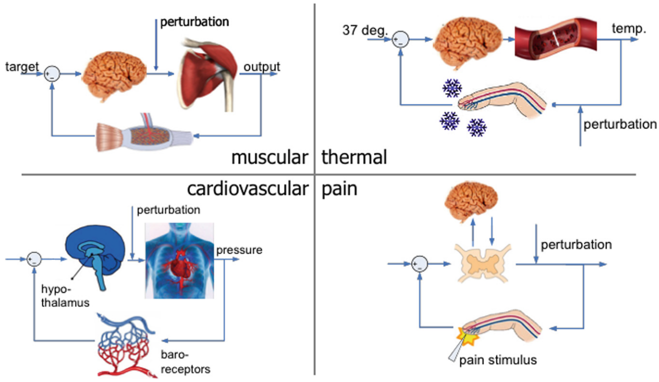


**Fig. 1.** The CNS controls body functions and initiates actions through an integrated system of multiple feedback loops. For example, the central nervous system (the ‘brain’) generates the motor commands for the muscles to initiate movement (upper left panel). Several sensory systems, like vision and proprioception provide feedback to the CNS, giving a closed-loop system.

intervention may be applied while for the latter case administration of anti-spastic drugs are to be chosen. System identification allows to unravel human motion control and can be crucial to uncover the mechanisms in movement disorders and to improve the clinical understanding and diagnosis of movement disorders.

The challenge is to assess the functioning of an intact feedback system in vivo, where cause and effect are intermingled. A closed-loop system identification approach is essential to assess the separate feedback loops of the CNS in an intact functional system. In the control engineering field, several techniques have been developed which deals with system identification of closed-loop systems. However, several existing techniques in measuring neurophysiological functions are based on an open-loop approach to the feedback loop, or only measure parts of the feedback loop, and therefore might lead to erroneous results [1–4].

In this paper we show the errors which can occur when estimated system dynamics using standard (open-loop) system identification algorithms in the presence of feedback loops. Furthermore, we show how these issues can be solved by using closed-loop algorithms.

## 2 Materials and Methods

Here, we simulated a system under feedback, see Fig. 2., using a perturbation signal to excite the closed-loop system and investigated the effect of noise on the estimated system dynamics. We assume the perturbation signal, $r(t)$, the system’s input, $u(t)$, as well as the system’s output, $y(t)$, are available for measurement. The system dynamics, $H$, were estimated with a standard (open-loop) nonparametric method, using the system’s input and output, and a closed-loop algorithm, also using the perturbation signal:

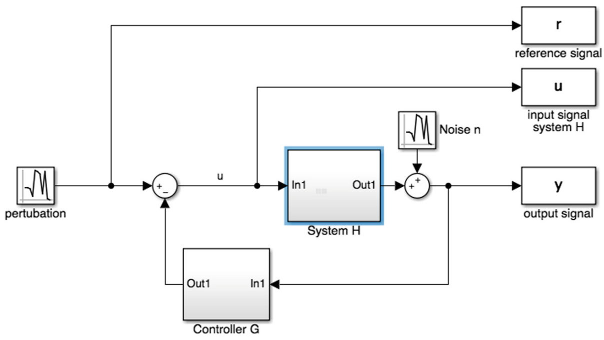


**Fig. 2.** Simulated closed-loop system, consisting of system $H$ and controller $G$. System $H$ is estimated using the system's input signal, *u(t)*, and output signal, *y(t)* (open-loop algorithm). Closed-loop algorithm also uses perturbation signal, *r(t)*. The perturbation signal, *r(t)*, is a white noise with unity variance; the noise, *n(t)*, is a white noise signal where several different noise variances are applied, see methods and Fig. 3.

$$\hat{H}_{OL}(f) = \frac{\hat{S}_{yu}(f)}{\hat{S}_{uu}(f)} \tag{1}$$

$$\hat{H}_{CL}(f) = \frac{\hat{S}_{yr}(f)}{\hat{S}_{ur}(f)} \tag{2}$$

In which $\hat{H}$ indicates the estimated Frequency Response Function (FRF), based on the estimated spectral densities, $\hat{S}$.

The system was simulated for 200 s and signals were recorded with a sample frequency of 100 Hz. The FRF was estimated using (1–2), where spectral densities were estimated with Welch' method (32 segments, no overlap, and a Hann window). The perturbation signal was a white noise with unity variance. We investigated the effect of (white) noise on the system's output.

## 3 Results

The estimated FRF of a system in closed-loop, using a standard, open-loop, system identification algorithm can result in erroneous results (i.e. an estimation bias) depending on the amount of output noise present, see Fig. 3. These issues are prevented by using closed-loop algorithms, see Fig. 4. For both algorithm the estimator variance increases with output noise, where the open-loop algorithm also results in an estimation bias.

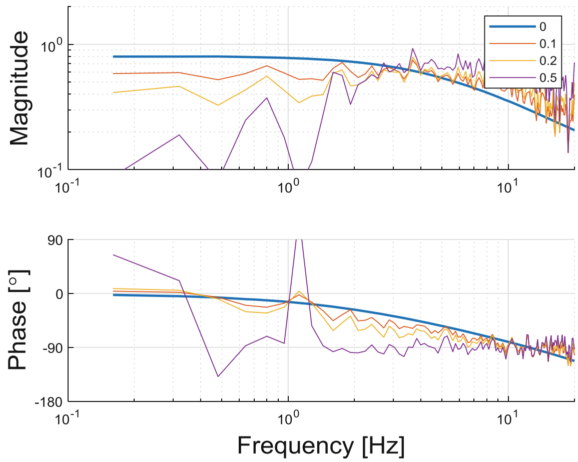


**Fig. 3.** The estimated frequency response function (FRF) using a standard, open-loop, algorithm under varies degrees of output noise variance, as indicated by the different lines. The estimated system with no noise (‘0’) overlaps the true simulated system.

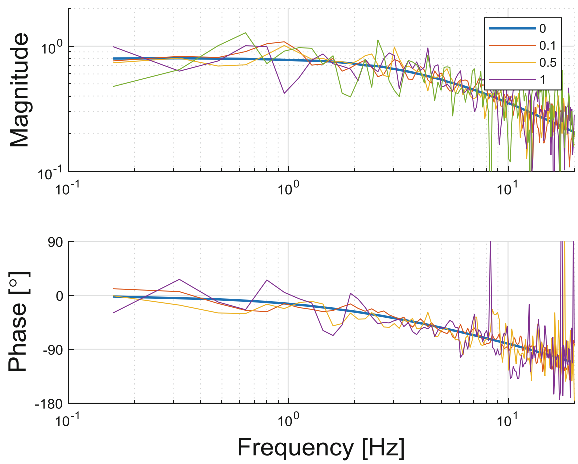


**Fig. 4.** The estimated frequency response function (FRF) using a closed-loop algorithm under varies degrees of output noise variance, as indicated by the different lines. The estimated system with no noise (‘0’) overlaps the true simulated system.

## 4 Discussion and Conclusion

System identification is an emerging tool in biomechanics, neuroscience and human motion control, for example to investigate and better understand the dynamics of the human neuromuscular system, which is crucial to unravel the pathophysiology of movement disorders [5–7]. Sensory feedback is crucial in human motion control to correct for internal and external disturbances and noises, making human motion control a closed-loop feedback system. A typical way to assess the behavior within a functional closed-loop is the application of dedicated perturbations; in human motion control typically with a robotic manipulator. When studying sensory feedback, it is essential to provide a known external perturbation and employ **closed-loop** system identification techniques to open the loop.

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