Metrics and Levels of Autonomy

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ABSTRACT

Autonomous vehicles have certainly captured the imagination of everyone. However, when people consider autonomous systems many times they mean different things. In this talk autonomy will be discussed and defined, metrics that are useful when comparing autonomy levels will be introduced and a functional hierarchical architecture for the control of autonomous systems will be discussed together with the role of control systems in autonomy.

SUMMARY

We need to have measures of the Levels of Autonomy to compare systems and decide whether our actions have increased or decreased the autonomy of a system. For this to be accomplished we need to agree upon a definition of autonomy. The term autonomy standing on its own without qualifications is vague. It is not unlikely the term optimal which can be vague if we do not specify some performance index and any imposed constraints; in fact, any action can be optimal with respect to some appropriate performance index! Similarly, autonomy should be defined with respect to certain goals to be accomplished under certain constraints due to uncertainties.

A simple definition that captures the essence of autonomy is as follows. A system is Autonomous with respect to a set of goals and under a set of uncertainties, if it has the capacity to accomplish all these goals in the presence of all these uncertainties. Or more precisely

If a system has the capacity to achieve a set of goals under a set of uncertainties in the system and its environment, by itself, without external intervention, then it will be called autonomous with respect to the set of goals under the set of uncertainties.

It follows that a system that can accomplish more goals under the same uncertainties has higher level of autonomy. Also, a system that can accomplish the same goals under more uncertainties has higher level of autonomy. An autonomous system always has goals to accomplish and this is to be done via some action to be determined and so every autonomous system can be regarded as a control system.

The autonomy level of a system can be manipulated and increased by adding feedback control, adaptation, learning, planning, failure detection and reconfiguration capabilities, which in effect increase the level of uncertainties the system can cope with autonomously.

A fixed feedback control system has low degree of autonomy, because it can achieve the stability goals under rather restricted parameter variations and external disturbances. When there are more substantial parameter changes then one could use methods from adaptive control to achieve stability. Such adaptive control system has higher degree of autonomy due to greater uncertainty in the parameters it can handle.

We will describe a conceptual functional architecture of the autonomous controller for the operation of future advanced space vehicles that was developed some time ago at JPL. This will show how autonomous systems can be seen as evolving from standard control systems. This hierarchical architecture is certainly one of many possible control architectures.

Our definition of autonomous behavior provides a natural way to define levels or degrees of autonomy via simple quantitative relations, specifically, \

{Measure of the Set of Goals} x {Measure of the Set of Uncertainties} = L,

where L is the level of autonomy. This easily leads to an intriguing and interesting relation, a simpler version of which is well known in control systems theory, namely

{Performance} x {Robustness} = L, the level of autonomy.

Here Performance is a measure of the set of goals that can be achieved (and it may include stability) and Robustness (Resilience) is a measure of the set of uncertainties under which the goals are reached. Systems with higher Performance and/or higher Robustness/Resilience have higher degrees of autonomy.

Entropy can be used as a general measure of the set of uncertainties. Entropy in autonomy will also be discussed here. An additional useful and interesting measure is the degree of external intervention needed to achieve the set of goals. The higher the needed external intervention the lower the level of uncertainties under which the goals can be achieved; that is there exists an inversely proportional relation between the level of needed external intervention and the level of uncertainties or robustness under which the system operates when achieving the set of goals.

Adaptive autonomy is interesting ad promising concept in that, systems (or humans and systems) negotiate and adjust accordingly their levels of autonomy. Future automobiles for example may negotiate with the human driver regarding the functions performed by the driver, who for example would like to take over the ABS or the stability control system functions.

Another interesting example is the case of an FDI system that identifies, for example, an aileron fault without providing additional details. Because of the uncertainties the goals may be reduced to just maintaining a safe flight. As details become available, e.g. aileron stuck at 10 degrees, the uncertainties are reduced and more goals can be accomplished.

The above definitions and metrics apply to human autonomy as well. We have designed cars, roads etc, so an average human driver can achieve the desired goals – e.g. going from point A to B safely – even under certain level of uncertainties induced, say, by bad weather where the input from our vision sensors may deteriorate. If the uncertainties increase significantly, e.g. under a snow storm, the goals may not be attainable. Uncertainties may be caused also by the lack of or limited knowledge of the process to be controlled. A human driver who wants to accomplish certain new goals can make it possible by reducing the uncertainties via training. An experienced human driver can accomplish more goals than an inexperienced driver. Uncertainties may be reduced by more and better sensors, by better knowledge of the process say via training, by methods to extract better information out of the data received, via say learning, by improving ways to act on the system based on better knowledge of the process – when a car loses its breaks it can still be stopped using the hand-break or by downshifting gears. An impaired human driver has to face increased uncertainties due to inability to process correctly and efficiently the sensor data received or inability to implement appropriate actions in a timely manner. So, the goals that could be accomplished in this case are greatly reduced.

It should be noted that the most recent published description of the above approach is in [1], where details of the hierarchical functional architecture are discussed and an extensive set of references is provided.

[1] Panos Antsaklis. "Autonomy and Metrics of Autonomy," Annual Reviews in Control, Vol. 49, pp. 15-26, 2020. https://doi.org/10.1016/j.arcontrol.2020.05.001