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Quantitative Cognitics and Agility Requirements in the Design of Cooperating Autonomous Robots

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Quantitative Cognitics and Agility Requirements in the Design of Cooperating Autonomous Robots

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1. Introduction 1 of 2

- **Automated processes - focus here on information-related flows and processes (not on energy, nor on materials).**
- **Nowadays, the latter are commonly automated, even when involving cognitive operations in complex and demanding applications.**
- **Novel formal definitions and units need be defined (re. knowledge, abstractions, learning, etc. - Quantitative cognitics), beyond the concept of information.**
- **This new need is widely recognized in many fields ranging from technical domains (e.g. in manufacturing workshops), to computer-based context and even further to social sciences and humanities areas (re. “dealing with complexity”). Assistance at home is one field of particular interest.**

1. Introduction 2 of 2

- **In order to progress in such areas, several contributions are presented in this paper.**
  - **In general, a quantitative approach is recommended (quantitative cognitics) ;**
  - **in particular, the estimation of knowledge for cognitive systems which sometimes make errors, is shown below.**
  - **Another point : agilities of controllers are critical factors for the design and stability of multi-agent systems (e. g. a group of robots, or a set of internal components of a single robot, or a mixed group of humans and robots).**
  - **The case of designing autonomous, cooperating robots, as well for Eurobot competitions as for domestic applications in Robocup-at-Home league , provides a good example where to dsicuss these concepts**

Content

2. Knowledge Estimation in Presence of Errors 1 of 4

- In MCS model [e.g. 2], the concept of knowledge is usually presented for the basic case, namely for the case of systems that deliver correct information; possibly limited to a small domain, but nevertheless always correct.
- Let us remind the reader of the MCS equation for assessing knowledge, K, which is the following:

$$K = \log_2\left(n_o \cdot 2^{n_i} + 1\right)$$ [lin] eq. 1

where n_i is the quantity of information entering the system, and n_o is the quantity of information delivered by the system.

2. Knowledge Estimation in Presence of Errors 2 of 4

- Equ. 1, includes, in its core, a quantity M, defined below, which can be viewed as the complexity of the process, or, in principle, as the size of a (virtual) memory containing all the possible messages delivered, for all possible input configuration (this memory is virtual, in the sense that in nearly all cases, it would be totally impossible to realize such a memory ; yet this is an interesting equivalent model, to be considered as a reference for quantitative assessment):

$$M = n_o \cdot 2^{n_i}$$ [bit] eq. 2

2. Knowledge Estimation in Presence of Errors 3 of 4

- **An extension is very useful for information flows that are not totally error-free.**
- **In such a case, on a given domain D_m, particular output messages, d_{osj}, do not necessarily correspond to the correct corresponding ones, d_{oj}.**
- **Equation 1 still applicable, but out-flowing information that does not correspond to D_m, i.e. "noise" or "error", should be removed from the equation.**
- **The quantity of correct information delivered by the system, n_{osc}, must then be estimated in each case, and injected into Equ. 1:**

$$M_s = n_{osc} \cdot 2^{n_i}$$ **[bit] eq. 3**

2. Knowledge Estimation in Presence of Errors 4 of 4

The quantity n_{osc} is defined in the following way:

$$n_{osc} = \sum_{j=1}^{n} p\left(d_{os\,j}\right) \cdot p\left(d_{os\,j} == d_{o\,j}\right) \cdot \log_2((p\left(d_{os\,j}\right))^{-1})$$ **[bit] eq. 4**

where

- **$p(d_{osj})$: probability of occurrence of message d_{osj} flowing out,**
- **d_{oj} : corresponding correct result, i.e. the result that belongs to the knowledge domain under consideration,**
- **$p(d_{osj} = d_{oj})$: probability of the jth output message to be correct.**

Basic idea here : the information quantity delivered by each output message must be weighted by its probability of being correct.

- **If answers all correct: second term on the right side has null effect (factor equal to 1); three quantities no, nos, and nosc will be the same.**
- **if answers all wrong, n_{osc} will be zero, leading to zero [lin] of knowledge, even if n_{os} is much larger than n_o.**

Content

3. Cognitive Quantities in Perception, Decision and Action Processes 1 of 2

- MCS model can describe as well human cognitive processes as those processes running on man-made systems.
- « Cognitic » rather than « cognitive » could be used, when relating specifically to man-made systems rather than to human beings.
- Quantitative estimations show that performance levels may not always lie where intuitively expected.
- Observing humans, the overall cognitive system could be validly considered as a single black box. It may also been useful to analyze things at a finer granularity level : perception, decision, and action.
- In general, perception processes imply much larger cognitic/cognitive quantities (in particular complexity and knowledge) than action, and, even more so, than decision.
- In A.I. however, attention tends to be focussed on decision processes, while for real-world systems, perception and action processes cannot be ignored.

3. Cognitive Quantities in Perception, Decision and Action Processes 2 of 2

Considering the elementary task of starting or stopping a car at a crossroad, as a function of red or green states of a traffic light, the following quantities may be estimated.

$$K_{decision} = \log_2\left(1 \cdot 2^1 + 1\right) \approx 1$$ **[lin] eq. 5**

$$K_{perception} = \log_2\left(1 \cdot 2^{30000} + 1\right) \approx 30'\ 000$$ **[lin] eq. 6**

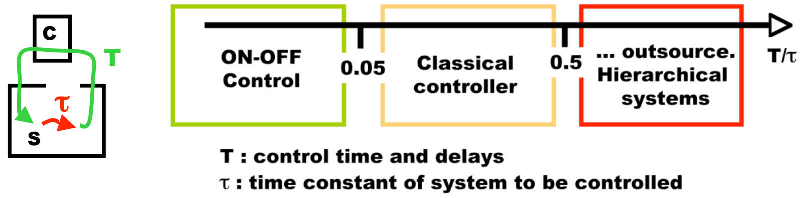
assuming a good enough traffic view, compatible in quality with what a 100 row x 100 column, color camera can acquire

$$K_{action} \approx \log_2\left(200 \cdot 2^1 + 1\right) \approx 10$$ **[lin] eq. 7**

assuming a 1 meter long trajectory to be travelled, with 1 cm accuracy, in 3-D space, for a leg actuating the gas or the brake pedals.

Content

4. Behavioral Stability of Groups 1 of 2



Control may be easy to be achieved, or quite impossible, depending on the relative agility of controllers

4. Behavioral Stability of Groups 2 of 2

- **It has been shown that the agility of closed-loop controllers, relative to the dynamic behaviour of systems to be controlled, is critical for success.**
- **In the case of multiple systems, such as a group of cooperating robots, interactions will usually occur, thus creating a potentially large number of individual, elementary control (decision) loops.**
- **For a successful overall system behaviour, it is critical that in all control (decision) loops, the relative agility be good enough. Taking the relative agility as an indicator provides a sound basis for task allocation and decision priorities in group negotiations.**

Content

5. Necessity of Time Modelling and Time Reference in Complex, Distributed, Multi-agent Systems 1 of 5

- **Interacting systems exchange information and thereby may yield numerous control loops.**
  - **The danger in those cases is that when systems grow, involving more agents and processes, the global, collective behaviour becomes unstable.**
  - **As shown in previous slides, an interesting indicator of the reliability of decision making in any considered loop is provided by the agility of the control (decision-taking) element, including communication delays, relatively to some dynamic properties of controlled system elements (characteristic time constant).**
- **Examples:**
  - **group of robots as in a soccer team, or the**
  - **water-circuit management resource of a warship, as presented by Rockwell Automation**

5. Necessity of Time Modelling and Time Reference in Complex, Distributed, Multi-agent Systems 2 of 5

- **In complex, distributed multi-agent systems,**
  - **the number of interaction loops may be very large, with very different agility features**
  - **the situation is even more difficult to manage if reconfigurations may dynamically occur.**
  - **in such cases it is difficult during design phase to forecast all possible configurations and to predefine all appropriate decision paths and units.**
- **In a soccer game for example instability will suddenly occur if a robot can move fast, but is controlled through an information path (loop) relatively slow, because of including communication through several team members.**

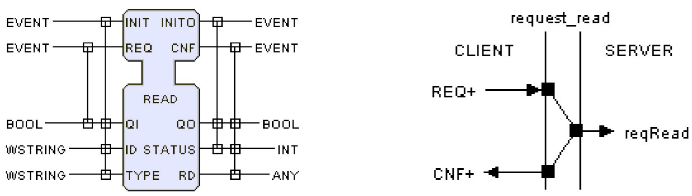
5. Necessity of Time Modelling and Time Reference in Complex, Distributed, Multi-agent Systems 3 of 5

- **Approaches worth to be considered include the following ones:**
  - **1. to characterize extensively signals (samples) in terms of phase (add accompanying time-stamps).**
  - **2. to dynamically identify the time responses of elements to be controlled (for all relevant loops).**
  - **3. to reduce as much as possible the occurrence of loops by organizing subsystems in as decoupled a way as possible (functional and topological autonomy).**
- **When feasible, approach 3 is drastic in avoiding loops and thereby the risk of instability. Approaches 1 and 2 allow applying in real-time the agility criterion mentioned in the previous paragraph for allocating instantaneous decision rights.**

5. Necessity of Time Modelling and Time Reference in Complex, Distributed, Multi-agent Systems 4 of 5

- **For example, in novel proposals for so-called intelligent control, such as in particular in O3NEIDA context a good basis is already provided:**
  - **the formalism of functional blocks (FB).**
  - **time is already explicitly taken into account in terms of sequence and causality.**
  - **An additional modelling step making *delays* explicit seems to be practically feasible for FB's and would provide the basis for robust, distributed behaviour in complex systems in this context.**
- **Other interesting examples (of similar problems to solve) are numerous in the domain of cooperating robots.**

5. Necessity of Time Modelling and Time Reference in Complex, Distributed, Multi-agent Systems 5 of 5



(a) (b)

Example of functional block in IEC61'499 framework (a), and example of associated elementary signal sequence (b). Time is already partially modelled – sequence – and now quantitative time attributes should be added.

Content

6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 1 of 13

- **This section relates to mobile, cooperating robots.**
  - **It presents and illustrates the general idea that**
  - **perception tasks are usually much more demanding, in cognitive performance levels,**
  - **than action and, even more so,**
  - **than decision tasks.**
- **It also helps demonstrating how MCS metrics can be practiced and proven useful.**

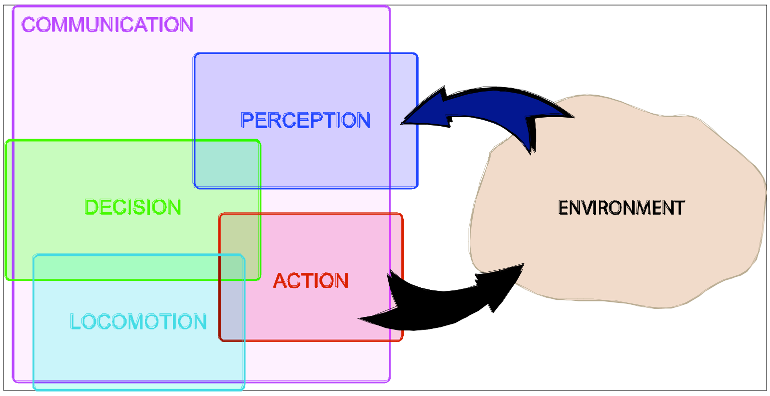
6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 2 of 13

- **RH3-Y, our mobile, cooperating robot for demonstrations in domestic applications. Blue trays, with individual covers, are there for user purpose, in « at home » applications. The lower level contains electrical and electronic devices, servo controller and PLC ; the supervision computer can be lying on top of the trays, for development phases, but is normally smaller and also confined in the lower part of the robot; or is replaced by a fixed, regular computer, operating remotely via Ethernet and TCP/IP connection.**

6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 3 of 13

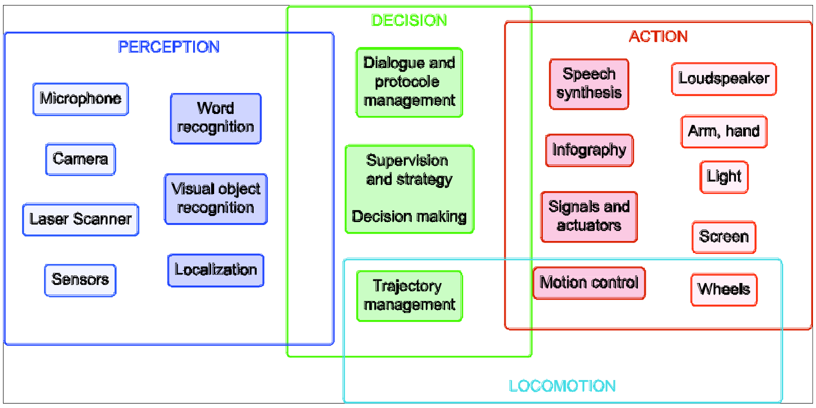
- **RH3-Y is the third version of our mobile, cooperating robot for demonstrations in domestic applications.**
- **Following previous designs for Eurobot, RH-Y robots have taken part in competitions and have for example proven capable, in principle, to follow a human, or to look for an object and fetch it back.**
- **E.g. to follow a person is a basic skill for many potential home applications:**
  - **carrying goods,**
  - **accompanying persons in order to be ready for services,**
  - **being trained for preferred paths,**
  - **etc.**

6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 4 of 13



Overview of main cognitive functions of a mobile, cooperating robot.

6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 5 of 13



Refined view of main cognitive functions and resources of RH2-Y (This robot is RH1-Y augmented by the addition of basic arm and « hand », among other improvements).

6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 6 of 13

- **The main cognitive processes can be more or less distributed in specialized functional units: perception (in particular word recognition, visual object recognition, obstacle localisation), decision, action, etc.**
- **Let's consider some specific tasks to be handled by RH-Y. In the context of Robocup-at-home, very precise tasks have been defined, and they are updated every year. There has been in particular, in 2006, a « navigation » task, which required in principle that the system visit 3 locations, according to user's choice, among about 10 specific predefined possible locations**
- **In order to have a convenient human-robot interaction, vocal dialogue is particularly well suited**

6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 7 of 13

- **As stated so far, and globally, the key quantities of information are the following:**
  - **as input of the system : about 10 bit, considering that we have 3 words, each one being equally probable among 10 possibilities.**
  - **here input and output quantities are the same, the cognitive process being purely to transfer on the output what is fed as input.**

$$n_i = n_o = \log_2(10) * 3 \approx 10$$ **[bit] eq. 8**

- **These input and output quantities provide the essential substance in order to qualify the necessary amount of knowledge required for the task as stated.**

$$K_{global} = \log_2\left(10 \cdot 2^{10} + 1\right) \approx 13$$ **[lin] eq. 9**

•13 lin is a small quantity.

6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 8 of 13

- **In practice, the global view is, schematically speaking, also the view at the level of the decision unit.**
- **However the user does not feed the decision unit with a nicely encoded, 10 bit signal. The user « just speaks », in English, with the restricted vocabulary mentioned (3 times one word among 10 possible topological names).**
- **Consequently, the robot needs a perception stage.**
  - **As shown on previous Fig., the sound path starts with a microphone, connected to the perception unit.**
  - **At the input interface of the latter, the amount of information received is about 50'000 bit per word. At least 150'000 bit for all three of them:**
    - **assume a 0.5 s duration per word,**
    - **10 kHz of sampling frequency, and**
    - **1% accuracy;**
    - **classical information theory.**

6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 9 of 13

- **When everything works perfectly, the three words (out of ten possible) are abstracted from the sound-wave, i.e. recognized, which means that about 10 bit of correct information is indeed delivered by the perception unit to the decision unit. (In case the recognition is not totally error-free, the equation of paragraph 2, above, should be taken)**
- **Thus the knowledge quantity required for the perception stage is the following:**

$$K_{WordPerception} = \log_2\left(10 \cdot 2^{150'000} + 1\right) \approx 150'000$$ **[lin] eq. 10**

6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 10 of 13

- **On the other hand, once decided, a destination location has still to be reached.**
- **Assuming:**
  - **10 cm accuracy,**
  - **average coordinated motion along a 5 m path,**
  - **to be done three times, and**
  - **a motion in the plane (3 degrees of freedom),**

  the action function has to concretely deliver (« synthesize ») about 2'500 [bit] of (correct) information in order to define the trajectory:

$$n_o = 3 \cdot \frac{5}{0.1} \cdot 3 \cdot \log_2\left(\frac{5}{0.1}\right) \approx 2500$$ **[bit] eq. 11**

- **Thus the knowledge quantity required for the action (or locomotion) stage is the following:**

$$K_{TrajectoryPlanning} = \log_2\left(2500 \cdot 2^{10} + 1\right) \approx 30$$ **[lin] eq. 12**

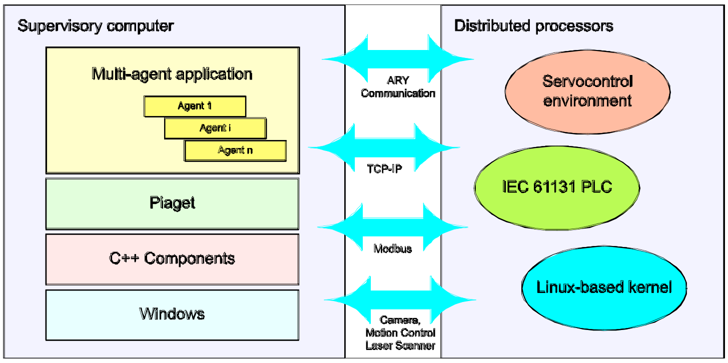
6. Case study – Quantitative Assessment of Cognitive Performance Levels for a Mobile, Cooperating Robot, in Domestic Environment 11 of 13

- **Looking back at Equ. 9 (decision alone), we can see that the estimation of knowledge required may not be realistic there.**
- **In the case we review, the input information is vocal, and on the output side a full trajectory is to be defined (and travelled).**
- **The perception stage and the action stage should not be overlooked.**
- **Consequently the following expression appropriately describes the amount of knowledge required for the task to be successfully performed:**

$$K_{global2} = \log_2\left(2'500 \cdot 2^{150000} + 1\right) \approx 150'000$$ **[lin] eq. 13**

The design of cognitic systems featuring such a large amount of knowledge is usually not obvious. The Fig. below gives an overview of the control resources and architecture adopted for the design of RH-Y.

Overview of the control resources and architecture of RH1-Y



- **It can be observed in the figure that a variety of embedded agents are used, in order to match very different time-scales:**
  - **supervisory computer for large-scope, relatively less agile control loops;**
  - **for more agility in reflex loops a PLC (re. IEC 61'131),**
  - **yet more agile servo controllers**
  - **specialized processors in smart sensors (in particular color camera, laser scanner).**
- **These various resources are interconnected but remain to a large extent autonomous.**
- **This is well in line with the measures proposed above:**
  - **adapting the agility of each controller to the specific requirements of the task they control;**
  - **keeping to a minimum level the amount of interaction between agents.**

Content

7. Conclusion 1 of 3

- The paper has presented several contributions to the field of cognitics and multi-agent systems.
- The first main contribution relates to a quantitative approach for cognitive systems, and shows in particular the importance of abstraction and concretization processes.
- Cognitive systems can be viewed as single black-boxes, processing information, However they can also be considered as structures where more detailed processes are present (or conversely as larger systems, such as a group of robots for instance).
- For humans or autonomous, cooperating robots, perception, decision, or, in a more refined fashion yet, vision or trajectory planning are good examples of (sub-) processes that can be addressed independently, as specific functions.

7. Conclusion 2 of 3

- **The MCS metric system is helpful in order to guide understanding and developments of cognitive systems,**

  Applying these metrics typically shows that
  - **the largest cognitive load is put on perception, then**
  - **much less is required for action, and**
  - **even less, for decision functions;**

  while by intuition people usually tend to refer mostly to the latter.
- **The second main contribution shows how**
  - **time and time-related properties are crucial indicators for the design and operation of complex, distributed, and in particular multi-agent systems.**
  - **For complex cases, many resources are necessary, a multi-agent structure may be useful, but then interactions occur and this implies loops where information flows, and consequently stability becomes increasingly of a concern.**

7. Conclusion 3 of 3

- **A critical property in every loop : the relative agility of control elements. Time and delays must be tracked, or at least represented in a model when tracking is not feasible, in order that decision power be allocated dynamically to the appropriate elements. Thus distributed, complex, multi-agent systems remain stable and effective. Another element of solution: reduce interactions and loops by isolating components, giving each of them as much autonomy as possible.**
- **In the third and final part a cooperating robot for domestic use has been presented, as a case study, and above concepts have been illustrated. In particular,**
- **vocal communication has been shown to be very demanding in cognitive terms and, with current implementation, does not always behave totally without errors.**
- **For such cases, the probability of error is to be taken into account so as to rightly estimate relevant knowledge quantities.**

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Thanks for the attention!

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References 1 of 2

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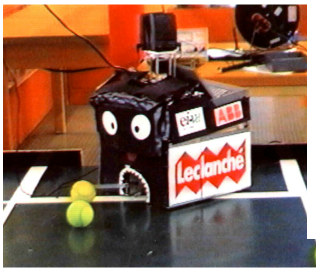
Main definitions and units in MCS

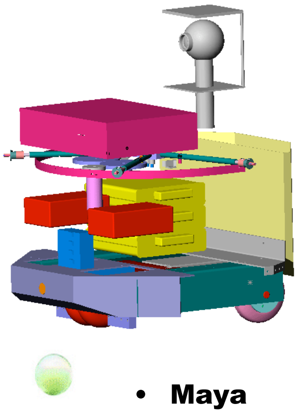
- **Information:** $n=\sum p_i \log_2(1/p_i)$ [bit]

- **Complexity of cognitive domain :** $L=n_{out}\, 2^{n_{in}}$ [bit]
- **Knowledge :** $K=\log_2(L)$ [lin]
- **Expertise :** $E=K/\Delta t$ [lin/s]
- **Learning :** $\Delta E=E(t_1)-E(t_0)$; >0 [lin/s]
- **Intelligence :** $I=\Delta E/\Delta n$ [lin/s/bit]

HEIG-VD Platforms for Eurobot

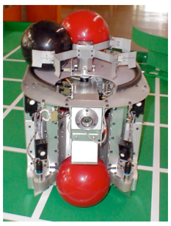
- **Diego3
1998, CH**





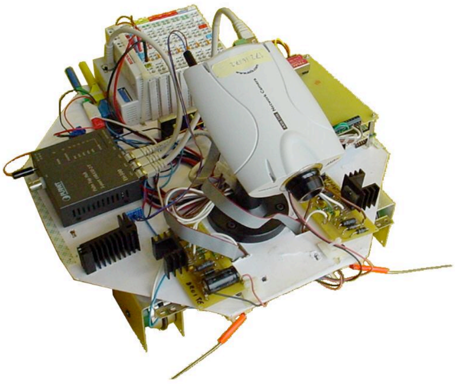
- **Arthur
1999, EU**
- **Maya
2000, EU**

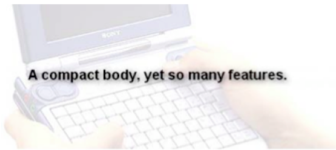
- **Alf 200
EU**



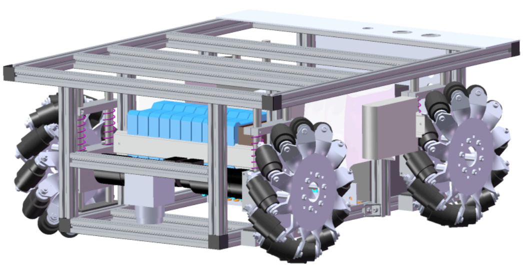
- **Hornuss
2003, CH**
- **PacMan
2002, EU**

HEIG-VD Platform - NewOne





HEIG-VD Platform – RH3-Y base4W



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