FUZZY DECISION MAKING FOR CONCEPTUAL DESIGN OF A VISUAL SERVOING SYSTEM USING MECHATRONIC MULTI-CRITERIA PROFILE (MMP)

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ABSTRACT

Mechatronic systems are of increased importance in engineering and their relevance goes hand in hand with the increasing complexity of the tasks they perform. Due to the inherent complexity of mechatronic systems, a concurrent systematic and multi-objective design thinking methodology is crucial to replace the often used sequential design approach that tends to deal with the different domains separately. In this research we present a new multi-criteria profile (MMP) for mechatronic system performance evaluation in the stage of conceptual design. Based on the assessed MMP for each of generated design concepts and using a method of aggregation for interacting criteria, a global performance index will be calculated. Best mechatronic configurations are determined by maximizing this performance index. In the presented paper two nonlinear fuzzy integrals called 2-additive Choquet and Sugeno will be used for the aggregation of criteria and fitting the intuitive requirements for decision-making in the presence of interacting criteria. Finally, the effectiveness of the proposed design method alongside each of the decision making models will be validated via a case study of designing a robotic visual servoing system. The comparative simulation results for the overall system performance will also be presented for both cases of using Choquet and Sugeno integrals.

1. INTRODUCTION

Mechatronic systems are combinations of cooperative mechanical, electronics and control components. The high number of their components, their multi-physical aspect, the couplings between the different domains involved and the interacting design objectives makes the design task very tedious ad complex [1, 2]. Design of a wide variety of products such as transportation systems, aircrafts, robots, construction machines or even home appliances are now considered within the area of mechatronic systems. Due to this inherent complexity and the dynamic coupling between subsystems of a mechatronic systems, a systematic and multi-objective design thinking methodology is crucial to replace the often used sequential design approach that tends to deal with the different domains (mechanical, electrical, software, fluid, thermal, etc.) separately. The results are products that would eventually form a special integration and a functional interaction in components, modules, products and systems.

Zhang et al. [3] proposed an integrated approach for mechatronic design of a programmable closed-loop mechanical system. They used an objective function to reduce the shaking force and moment and consequently to facilitate the design of the control system. As an improvement to this work, Li et al. [4] developed a concurrent design framework known as design for control (DFC). Their idea was founded on the basis that, although controller parameters could be changed after the machine is built, they should be designed simultaneously with the structural parameters. Same as [3], to facilitate controller design, the reduction of the shaking force/moment of the actuators, was the only objective they considered for their method. Although an effective concurrent approach was introduced in their work, improving the system performance using changeability of the controller parameters has been overlooked. Yet, other important criteria in the evaluation of design have not been considered in their research. Seo et al. [5] developed an automated mechatronic design methodology using the integration of genetic programming and bond graph modelling, where only the structural part of the mechatronic system is considered and the controller part, which is always present in a mechatronic system, is missing. Furthermore, the performance of the design is measured only by physical parameters.

A number of problems and limitations are encountered when design in early stages which requires selection of components and choosing between alternatives for software and control strategies [6]. This part of conceptual and preliminary design is usually known as choosing the “Elite Set”. This practice creates a number of problems and limitations due to insufficient support of the multi-criteria nature of mechatronics systems design, which calls for decision support across various disciplines. In such cases, engineers tend to choose the first and the best
components from what they see as available and feasible to meet their design requirements. Such decisions can often lead to a functional design, but rarely to an optimal one. This ill decision making generally occurs due to improperly-defined performance criteria and lack of knowledge about the co-influences between criteria and the functionality to be provided by neighbouring disciplines. Moulianitis et al. [7] proposed a methodology for decision making in conceptual mechatronic design based upon an evaluation index including three criteria: intelligence, flexibility, and complexity. Weight factors were applied to highlight the importance of each criterion. The formulation of the evaluation score has been presented based on t-norm and averaging operators. However, the methodology does not consider interactions between criteria and a limited, discrete search space was considered. De Silva [8] stated that in a sequential design approach for mechatronic systems, optimal design of subsystems does not necessarily provide the optimum overall configuration. He proposed to associate performance indices to the mechatronic subsystems within an indicator, called “mechatronic design quotient (MDQ)” and maximizing this indicator after integrating all the subsystems.

Based on this method, Bebbahani [9] proposed a formal and systematic framework for design of a mechatronic system by using the concepts of mechatronic design quotient (MDQ) in a concurrent design approach, where correlation between design criteria have been taken into account by using fuzzy concepts to define the correlation factors. The methodology of MDQ was implemented in pilot projects [10], and has proved to be efficient; however measurement and determination of criteria for design are more qualitative and no systematic measurement approach has been presented. For the same purpose of performance analysis in conceptual design, Ferreira [11] proposed using neural networks as a decision support to recommend design solutions based on earlier successful designs. Similarly, Hammadi et al. [12] defined a multicriteria performance indicator as a neuronal network of radial basis functions for early stages of design of mechatronic systems.

In this paper, a new index vector called “Mechatronic Multicriteria Profile (MMP)” is introduced for the purpose of concept evaluation in mechatronic design. MMP includes five main criteria for a mechatronic system and can be determined numerically through mathematical functions which themselves include sub-criteria and reflect an aggregated value for each main criterion. Two nonlinear fuzzy integrals called 2-additive Choquet and Sugeno are then used for the aggregation of criteria by accommodating possible interactions. Finally, the performance of the proposed method is validated by applying it to conceptual design of a visual servoing system for a 6-DOF robotic manipulator. A comparison between the selected concepts by using Choquet and Sugeno integrals is also presented through simulation results.

2. MECHATRONIC MULTICRITERIA PROFILE (MMP)

Mechatronic system design mainly deals with the optimal and integrated design of various machines and parts which consist of cooperative mechanical, electronics, software and control components. Although mechatronic design companies recognize the difficult task of finding the right criteria to concurrently evaluate and synthesize their designs, there is still no systematic approach to do aid this activity. Being multi-criteria problematic, mechatronic systems design leads to Pareto decisions and achieving optimal solutions is a very complex if not impossible task without the identification of the performance parameters involved and the understanding of their co-influences. Optimal mechatronics design simultaneously requires a precise and systematic design evaluation stage. It is quite important to take into account both correlation between system requirements and also interactions between the multidisciplinary subsystems. In a conceptual design stage and based on sets of design specifications and goals, candidate solutions are generated (Fig. 1). In most of design projects, more than one candidate solutions is generated and evaluated in order to select the best one meeting the design objectives and constraints. Design evaluation consists of both comparison and decision making [13].

\[
\begin{bmatrix}
  MIQ \\
  RS \\
  CX \\
  FX \\
  CT \\
\end{bmatrix} 
\]

In which MIQ is the machine intelligence quotient, RS is the reliability score, CX is the complexity, FX is the flexibility and CT is cost of manufacture and production. It is important to note that \( m_i \) are the values for the members of MMP sorted in ascending order such that \( m_1 \leq m_2 \leq \ldots \leq m_j \) and \( 0 \leq m_i \leq 1 \).
2.1. MACHINE INTELLIGENCE QUOTIENT

Bien [14] and Kim [15] introduced the machine intelligence quotient (MIQ) as an index used to assess the intelligence of a control system in mechatronic machines. This index significantly differs from other well-known indices such as control performance, reliability, fault diagnosis capability, etc. MIQ and its concept and definition are still controversial subjects of major research and studies. The term MIQ used in the newly introduced MMP will be assessed based on a method presented by park et al. [16] in which the machine intelligence is divided into two components of control intelligence and interface intelligence. Accordingly, the mechatronic system was modeled using an intelligent task graph (ITG). In the topics related to parallel processing and scheduling, the set of tasks and their data dependencies are usually described by Data Flow Graph (DFG). They modified the DFG from the viewpoint of intelligence and transformed it into the ITG, which is suitable for analyzing the machine intelligence. Fig. 2 shows an example of the ITG in which the circles denote the tasks of control jobs and the directional arc denotes information flow from one task to another.

![Example of intelligent task graph (ITG) [16]](image)

Based on the work done by Park et al. [16] we will calculate the term MIQ for the presented mechatronic multicriteria profile (MMP). With regards to an ITG, a task set $T = \{T_1, T_2, ..., T_n\}$ is the set of n tasks required to control events. In a set of task intelligence costs, $\tau = \{\tau_1, \tau_2, ..., \tau_n\}$, $\tau_i$ is the intelligence required to execute $T_i$. Accordingly, in a data transfer matrix $F$, $f_{ij}$ is the data quantity transferred from $T_i$ to $T_j$, such that:

$$F = \begin{pmatrix}
0 & f_{12} & f_{13} & ... & f_{1n} \\
f_{21} & 0 & f_{23} & ... & f_{2n} \\
f_{31} & f_{32} & 0 & f_{34} & f_{3n} \\
... & ... & ... & ... & ... \\
f_{n1} & f_{n2} & f_{n3} & ... & 0
\end{pmatrix} \quad (2)$$

The complexity of transferring one unit of data between the human and the machine using user interface devices such as: displays, keyboards, control switches, mouse, etc. is called interface complexity in which $c_{ih}$ is the interface complexity of transferring data from the human to the machine, and $c_{mh}$ from the machine to the human. Interface intelligence cost $f_{ij}$, $c_{ih}$, and $f_{ij}c_{mh}$ are the human intelligence amount required to communicate data with the machine, which is proportional to both data quantity and interface complexity.

In a task allocation matrix, $A$, $a_{i1} = 1$, if the machine performs task $T_i$, and $a_{i2} = 1$ if the human performs task $T_i$. If $T_i$ can be assigned to neither the machine nor the human, $a_{i3} = 1$. Thus:

$$a_{i1} + a_{i2} + a_{i3} = 1 \quad (3)$$

For $\forall i, 1 \leq i \leq n$, the n by 3 matrix $A$ is defined as:

$$A = \begin{pmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
... & ... & ... \\
a_{n1} & a_{n2} & a_{n3}
\end{pmatrix} \quad (4)$$

The CIQ (control intelligence quotient) is defined as the sum of all task intelligence costs:

$$CIQ = \sum_{i=1}^{n} a_{i1} \cdot \tau_i + \sum_{i=1}^{n} a_{i2} \cdot \tau_i \quad (5)$$

The human intelligence quotient (HIQ) as the required intelligence quantity from the human for controlling plants is defined such as:

$$HIQ = (\sum_{i=1}^{n} a_{i2} \cdot \tau_i) + (c_{ih} \sum_{i=1}^{n} a_{i1} a_{i2} f_{ij}) + (c_{mh} \sum_{i=1}^{n} a_{i2} a_{i3} f_{ij}) \quad (6)$$

Finally, The MIQ can be calculated as follows:

$$MIQ = CIQ - HIQ. \quad (7)$$

2.2. RELIABILITY

System reliability assessment (SRA) has been addressed as an important issue of the design process of mechatronic systems in many literatures [17, 18]. A number of methods for reliability assessment have been developed, most of which estimate the system reliability using only the data of components [19]. The methods of fault tree analysis (FTA) and failure modes and effect analysis (FMEA) are the most popular tools for reliability assessment, while some other research have been established based upon using Petri nets (PN) for modeling of dynamic characteristics of complex mechatronic systems [17]. In the presented approach and in order to avoid complexity in assessing MMP for various design concepts, we did not take into account dynamic effects for reliability assessment and the following simple equation evolved as reliability score (RS):

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\[ RS = 1 - \sum_{i=1}^{n} p_i \]  

In which \( p_i \) is the failure probability of \( i^{th} \) component and \( m \) is the number of components in the mechatronic design concept.

### 2.3. Complexity

By modifying and expanding the work presented in [7], we introduce a new complexity vector as follows:

\[ \Phi = \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \varphi_6 \end{bmatrix} \]  

In which \( \varphi_1 \) is the quantity of components, \( \varphi_2 \) is the degree of architecture complexity (number of interconnections), \( \varphi_3 \) is the design backtrack to the earlier stages (number of feedback loops in design process), \( \varphi_4 \) is the number of distinct knowledge bases, \( \varphi_5 \) is the controller complexity (number of closed loops in all control strategies used in the system) and finally \( \varphi_6 \) is the extent of embedded software in product and depends on the degree of the system intelligence such that:

\[ \varphi_6 = 1 - \frac{MHQ}{M} \]  

After determination and normalization of \( \Phi \), and by using a linear summation of weighted factors, the complexity value of the concept will be assessed as follows:

\[ CX = \sum_{i=1}^{n} w_j \varphi_j \]  

where \( w_j \) are the weights associated to the complexity components.

### 2.4. Flexibility

Similar to what has been presented as complexity, a vector of design flexibility for a mechatronic concept is presented as follows:

\[ \Psi = \begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} \]  

In which \( \psi_1 \) is the number of alternative component design paths, \( \psi_2 \) is the number of customization options for components and \( \psi_3 \) is the number of choices for system architecture. After determination and normalization of \( \Psi \), the flexibility score for the corresponding concept can be calculated as:

\[ FX = \sum_{j=1}^{n} \rho_j \psi_j \]  

From Eq. 11 and Eq. 13, \( w_j \) and \( \rho_j \) are the weighting factors considered by the designer.

### 2.5. Cost

The cost (CT) member of mechatronic multicriteria profile (MMP) can be calculated and normalized based on summation of prices of all subsystems and cost of production and manufacture.

### 3. Global Concept Score (GCS) and Aggregation of Criteria

After specifying the weighting factors for all subsets of criteria, a 2-additive Choquet integral [20, 21] and also a Sugeno fuzzy integral [22] can be used to compute a global concept score in order to enable the designer to compare between the feasible generated design concepts.

The weighting factor of a subset of criteria is represented by a fuzzy measure on the universe \( N \) satisfying the following fuzzy measures (\( \mu \)) equations:

\[ \mu(\emptyset) = 0, \quad \mu(N) = 1. \]  

\[ A \subseteq B \subseteq N \Rightarrow \mu(A) \leq \mu(B) \]  

Where \( A \) and \( B \) represent the fuzzy sets.

#### 3.1. Sugeno Aggregation

Using a Sugeno fuzzy integral as a method of aggregation of interaction criteria can yield to a relative global concept score (GCS) as follows:

\[ GCS = S_n(m_1, m_2, ..., m_n) \]  

\[ = \sqrt[n]{m_1 \mu(A_{ij})}. \]  

Where \( (\cdot) \) indicates a permutation on \( N \) such that \( m_1 \leq m_2 \leq \ldots \leq m_n \). Also, \( \wedge := \min \) and \( \vee := \max \). Furthermore \( A_{ij} = \{i, \ldots, n\}, \) and \( A_{(n+1)} = \emptyset \).

#### 3.2. Choquet Aggregation

Choquet integral provides a weighting factor for each criterion, and also for each subset of criteria. Choquet integrals are a very effective way to measure an expected utility when dealing with uncertainty, which is the case in design in general and mechatronic design in particular. The global concept score (GCS) with regards to Choquet aggregation is defined as follows:

\[ GCS_c = C_n(m_1, m_2, ..., m_n) \]  

\[ = \sum_{i=1}^{n} \phi(\mu,i)m_i - \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} I(\mu,ij)|m_i - m_j| \]  

In which \( \phi(\mu,i) \) is the importance of criterion \( i \) and computed by the Shapley value (\( \phi \)) [20], which is defined as:

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\[ \phi(\mu, i) = \sum_{T \subseteq \mathcal{N}_0} \frac{(n-t-1)!t!}{n!} [\mu(T \cup i) - \mu(T)]. \]  

(18)

Where \( T \) is a subset of criteria. Furthermore \( I(\mu, ij) \) is the interaction index between criteria \( i \) and \( j \) and defined as follows:

\[ I(\mu, ij) = \sum_{T \subseteq \mathcal{N}_0, ij} \frac{(n-t-2)!t!}{(n-1)!} [\mu(T \cup ij) - \mu(T \cup i) - \mu(T \cup j) + \mu(T)]. \]  

(19)

It is important to note that desired overall importance and the interaction indices are satisfied during identification of fuzzy measures.

After assessing global concept score (GCS) for each design alternative, the concept selection can be performed to choose the best available design concept and consequently, in an iterative manner a modification can be applied to the selected concept and subsystems. Based on the requirements and objectives defined in the first stage, a more precise concept selection can be performed and after a few iterations the final decision for the conceptual design can be made. The procedure of conceptual design using the proposed methodology and based on the calculated global concept score is described in flowchart shown in Figure 3.

Figure 3: Conceptual Design of a Mechatronic System based on MMP and Global Concept Score (GCS)

4. CASE STUDY: DESIGN OF A ROBOTIC VISUAL SERVOING SYSTEM

Robotic systems and automation machineries have been increasingly employed in various industrial, urban and exploratory applications during last decades. However, robotic systems are generally limited to operate in highly structured environments. Thus, integration of vision sensors with robotic systems and generally “visual servoing” systems helped solve this problem by producing non-contact and wide measurements of the working area for the machine [23]. As a case study of using mechatronic multicriteria profile (MMP), conceptual design of a robotic visual servoing system for a 6 DOF manipulator robot for the task of catching a moving object is presented here. Fig. 3 shows a schematic diagram of the aforementioned robotic visual servoing system and its components.

The described robot visual servoing system consists of main components of: a 6-DOF manipulator mechanism with end-effector, vision rig holders, actuators and position sensors, multi-camera vision system, visual servo controller, motion controller and etc. The design objective here is to design a robotic visual servoing system which is capable of tracking and catching a moving object with the maximum mass of 1 kg and maximum velocity of 1 m/s within 3 seconds after the object enters the vision system’s line of sight and also within the area of motion with dimensions of 500mm×500mm×500mm.
Based on the defined objective, the concept selection and design should be performed upon deciding upon the mechanical structure and mechanism, actuators, vision sensors, and controllers, as the most essential components of the system.

Generation of design concepts and alternatives is described in Figure 5 and Table 1. This generation of design alternatives is performed after identification of objectives and feasible subsystems and components by the designer. Thus, the main objective of the decision-making task in conceptual design is to select, between all possible alternatives, the mechanism and actuator type, material and controllers that better matches the design objectives.

Based on the material used, the robot mechanism and end-effector selected for one specific concept, and also object’s mass and motion, the total mass and motion trajectory of the robot can be estimated. Consequently, the required power, payload, maximum allowable inertia moment, force and bandwidth can be also be easily estimated. An approximation of the total cost can also be identified based on the components and manufacturing process. Table 2 briefly gives the results for the estimated values for presented concepts. Details are not presented in this paper but are available upon request.
4.1. ASSESSMENT OF MMP

4.1.1. Machine Intelligence Quotient

In order to measure the machine intelligence quotient (MIQ) based on the proposed method in 2.1, two ITG models for a position-based visual servoing (PBVS) and an image-based visual servoing (IBVS) are considered and depicted in Figure 6-7.

![Figure 6: ITG model for a position-based robot visual servoing (PBVS) scheme](image)

![Figure 7: ITG model for an image-based robot visual servoing (IBVS) scheme](image)

Task intelligence cost, data transfer quantity, and interface complexity for both cases are measured and listed in Table 3.

Table 3: Parameters required for assessing MIQ for two cases of PBVS and IBVS

<table>
<thead>
<tr>
<th>PBVS</th>
<th>IBVS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_{pb} = {a_1, \ldots, a_6, \ldots, a_{10}} ) &amp; ( \tau_{ib} = {a_1, \ldots, a_6, \ldots, a_{10}} )</td>
<td></td>
</tr>
<tr>
<td>( c_{mk} = 0.07 ) &amp; ( c_{mk} = 0.08 )</td>
<td></td>
</tr>
<tr>
<td>( c_{m}\text{m}<em>k = 0.08 ) &amp; ( c</em>{m}\text{m}_k = 0.08 )</td>
<td></td>
</tr>
</tbody>
</table>

The MIQ for the case of using a PBVS approach can be calculated as follows through Eqs. 19 - 21.

\[
CIQ_{pb} = \sum_{i=1}^{n} a_{i1} \tau_i + \sum_{i=1}^{n} a_{i2} \tau_i = (r_2 + r_3 + r_4 + r_5 + r_6 + r_7) + (r_1 + r_2 + r_3) = 92
\]

\[
HIQ_{pb} = (\sum_{i=1}^{n} a_{i1} \tau_i) + (c_{mk} \sum_{i=1}^{n} a_{i1} a_{i2} f_{ij}) + (c_{m}\text{m}_k \sum_{i=1}^{n} a_{i1} a_{i3} f_{ij})
= (r_1 + r_2 + r_3) + c_{mk} (f_{30} + f_{3y} + f_{3h} + f_{3s} + f_{3a} + f_{3m})
+ c_{m}\text{m}_k (f_{12} + f_{14} + f_{15} + f_{16} + f_{17} + f_{19} + f_{1b})
= 31 + (0.07)(1.81 + 0.08)(289) = 66.79
\]

\[
MIQ_{pb} = CIQ_{pb} - HIQ_{pb} = 92 - 66.79 = 25.21
\]

The same procedure can be used to calculate the MIQ for the case of using an IBVS approach.

\[
CIQ_{ib} = \sum_{i=1}^{n} a_{i4} \tau_i + \sum_{i=1}^{n} a_{i5} \tau_i
= (r_2 + r_3 + r_4 + r_5 + r_6) + (r_1 + r_2 + r_3) = 91
\]
Thus the measures are already associated to the complexity components, which leaves 32=30 measures to be specified. The fuzzy measures used in the presented case study are shown in Table 6. They were obtained in an intuitive manner by the authors (all specialized in mechatronic design). The starting point of the values was first obtained by comparing the possible scenarios to what was found in literature [9, 16, 20, 21].

### 4.1.4. Flexibility Assessment

Table 4 shows the final results for flexibility assessment based on the proposed method in 2.4, where \( \Psi_i \) are the flexibility scores and \( \Phi_i \) are the normalized values which \( 0 \leq \Phi_i \leq 1 \). \( \rho_i = [0.4, 0.2, 0.4] \) are the weights associated to the flexibility components.

<table>
<thead>
<tr>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
<th>Concept 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Psi_i )</td>
<td>( \Phi_i )</td>
<td>( \Psi_i )</td>
<td>( \Phi_i )</td>
</tr>
<tr>
<td>[16]</td>
<td>[0.5]</td>
<td>[32]</td>
<td>[1]</td>
</tr>
<tr>
<td>[2]</td>
<td>[0.5]</td>
<td>[24]</td>
<td>[1]</td>
</tr>
<tr>
<td>[1]</td>
<td>[0.33]</td>
<td>[18]</td>
<td>[0.75]</td>
</tr>
<tr>
<td>[4]</td>
<td>[0.67]</td>
<td>[6]</td>
<td>[0.5]</td>
</tr>
<tr>
<td>[32]</td>
<td>[1]</td>
<td>[12]</td>
<td>[1]</td>
</tr>
<tr>
<td>[1]</td>
<td>[0.78]</td>
<td>[1]</td>
<td>[0.5]</td>
</tr>
<tr>
<td>[1]</td>
<td>[0.75]</td>
<td>[0.75]</td>
<td>[0.5]</td>
</tr>
<tr>
<td>[1]</td>
<td>[0.05]</td>
<td>[0.75]</td>
<td>[0.5]</td>
</tr>
<tr>
<td>[0.16]</td>
<td>[0.5]</td>
<td>[0.5]</td>
<td>[0.5]</td>
</tr>
</tbody>
</table>

### 4.2. AGGREGATION OF CRITERIA AND ASSESSMENT OF GLOBAL CONCEPT SCORE

The five elements of MMP form \( 2^5 = 32 \) possible subsets of criteria. Thus, 32 fuzzy measures should be carefully specified. Two of these measures are already defined by Equation (14) which leaves 32-2=30 measures to be specified. The fuzzy measures used in the presented case study are shown in Table 6. They were obtained in an intuitive manner by the authors (all specialized in mechatronic design). The starting point of the values was first obtained by comparing the possible scenarios to what was found in literature [9, 16, 20, 21]. Table 7 shows the results for the assessed MMP elements and global concept scores related to Choquet and Sugeno aggregations (GCSc, GCSc) for each generated concept and design alternatives for a robotic visual servoing system.

<table>
<thead>
<tr>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
<th>Concept 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_i )</td>
<td>( \mu_{12} )</td>
<td>( \mu_{13} )</td>
<td>( \mu_{14} )</td>
</tr>
<tr>
<td>0.6</td>
<td>0.55</td>
<td>0.45</td>
<td>0.4</td>
</tr>
<tr>
<td>0.25</td>
<td>0.5</td>
<td>0.75</td>
<td>0.45</td>
</tr>
<tr>
<td>0.15</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.2</td>
<td>0.05</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>0.15</td>
<td>0.1</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 7: Normalized MMP elements and global concept scores (GCSc) for design alternatives
As it can be concluded from the calculated GCS, the best selected concept corresponds to the second design alternative in which Aluminum is selected as the structure material and a 3R robot mechanism with DC Servo motors is used along with a proper end-effector. The selected visual servoing scheme is an Image-based system (IBVS) with a proportional-integral (PI) controller.

4.3. COMPARISON OF RESULTS

Based on the results achieved for global concept score, concept no.1 has been chosen to be the best design by using Sugeno integral, and by using Choquet integral the results yield to choosing concept no. 2. Based on the selected elements and parameters in Table 1 and 2, a simulation of a visual servoing system on a 6-DOF robot has been performed to validate the conceptual design decision making. Besides the materials and actuator types, the difference between the selected concepts mostly lies on the camera configuration (stereo vs. mono) and controller (proportional vs. proportional-integral). Fig. 8 shows the simulation results for a visual servoing system designed based on concepts no.1 and no.2. The servoing task consists of coinciding four image feature to four desired predefined points in image plane. The initial and desired configuration of the image features for each test are given in Table 8.

Table 8: Initial (IR, IL) and desired (DR, DL) location of feature points in pixel for Right and Left images

<table>
<thead>
<tr>
<th>Case</th>
<th>Point 1 (x, y)</th>
<th>Point 2 (x, y)</th>
<th>Point 3 (x, y)</th>
<th>Point 4 (x, y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td>398</td>
<td>510</td>
<td>580</td>
<td>331</td>
</tr>
<tr>
<td>IL</td>
<td>259</td>
<td>511</td>
<td>441</td>
<td>334</td>
</tr>
<tr>
<td>DR</td>
<td>641</td>
<td>812</td>
<td>600</td>
<td>489</td>
</tr>
<tr>
<td>DL</td>
<td>476</td>
<td>819</td>
<td>432</td>
<td>488</td>
</tr>
</tbody>
</table>

4.3. COMPARISON OF RESULTS

Based on the results achieved for global concept score, concept no.1 has been chosen to be the best design by using Sugeno integral, and by using Choquet integral the results yield to choosing concept no. 2. Based on the selected elements and parameters in Table 1 and 2, a simulation of a visual servoing system on a 6-DOF robot has been performed to validate the conceptual design decision making. Besides the materials and actuator types, the difference between the selected concepts mostly lies on the camera configuration (stereo vs. mono) and controller (proportional vs. proportional-integral). Fig. 8 shows the simulation results for a visual servoing system designed based on concepts no.1 and no.2. The servoing task consists of coinciding four image feature to four desired predefined points in image plane. The initial and desired configuration of the image features for each test are given in Table 8.

Table 8: Initial (IR, IL) and desired (DR, DL) location of feature points in pixel for Right and Left images

<table>
<thead>
<tr>
<th>Case</th>
<th>Point 1 (x, y)</th>
<th>Point 2 (x, y)</th>
<th>Point 3 (x, y)</th>
<th>Point 4 (x, y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td>398</td>
<td>510</td>
<td>580</td>
<td>331</td>
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<tr>
<td>IL</td>
<td>259</td>
<td>511</td>
<td>441</td>
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<td>DR</td>
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<td>812</td>
<td>600</td>
<td>489</td>
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<tr>
<td>DL</td>
<td>476</td>
<td>819</td>
<td>432</td>
<td>488</td>
</tr>
</tbody>
</table>

Figure 8 – (a) model of a multi-camera visual servoing system. Image feature trajectories in (b) concept 1: Monocular IBVS with P controller, (c,d) concept 2: Stereo IBVS with PI controller. (e,f) camera frame velocity in systems based on concept 1 and 2. As shown in Figure 8 the visual servoing system designed based on concept 1 has a better performance due to using a stereo vision system which enables the controller to precisely calculate the image Jacobian matrices. The feature trajectories are almost straight lines and the overall joint velocity for the end effector starts at a relatively smaller value.

5. CONCLUSION

In this paper a new multi-criteria profile (MMP) for mechatronic system performance evaluation in conceptual design stage has been introduced and the methods for assessment of the elements have been presented. The newly introduced Mechatronic Multi-criteria Profile (MMP) consists of five main design criteria such as intelligence, reliability, complexity, flexibility and cost and can be embedded in automated design routine. Based on the MMP for each concept and using a 2-additive Choquet Integral and also a Sugeno fuzzy integral, a global concept score (GCS) has been calculated to ease the procedure of concept selection and consequent concept modification. At the end, the proposed method has been applied to a case study of designing a robotic visual servoing system and the output selected concepts has been tested and compared using a computer simulation of a visual servoing task. The concept which achieved the highest Choquet-GCS has shown better performance due to taking into account both importance and interactions between multiple design criteria.

6. REFERENCES


