Design Optimization of Haptic Devices- A Systematic Literature Review

Xuan Sun, Kjell Andersson, and Ulf Sellgren

Abstract—Performance requirements for high-performing haptic devices are usually multi-criteria. Sometimes the requirements are interacting, and several of them are conflicting. Optimization is one of the main approaches to scrutinize the design space and to search for a design that satisfies all requirements. Many researchers have used and published optimization approaches to search for an optimal haptic device design. However, predicting the performance of a high-performing haptic device usually involves computationally intensive simulations and analyses with complex and heterogeneous models. In order to study what are the common design and performance requirements of haptic devices and what optimization approaches have been used to improve optimization effectiveness and efficiency, a literature review on the present state-of-the-art in these areas has been performed. The most commonly used performance requirements presented in the literature are the number of degrees-of-freedom, dynamic inertia, kinematic isotropy, stiffness, peak and continuous force, position/force resolution, and bandwidth. Furthermore, parallel and hybrid kinematic structures are more commonly used than serial structures. Multi-objective optimization (MOO) is a commonly used approach to simultaneously optimize all performance criteria. The most common optimization targets, as presented in published literature, are to maximize workspace, kinematic isotropy, as well as the peak force/torque provided by the device, and to minimize the dynamic inertia. Commonly used indices to constrain the design space are a minimum workspace, avoidance of singularities and motion limits of active and passive joints. The number of design variables varies from 2 to 9, and the most commonly used design variables are a set of mechanical parameters, such as the lengths and diameters of the mechanical components. To increase the efficiency of complex and multi-criteria optimization tasks, the Pareto-front approach combined with multidisciplinary design optimization (MDO) and metamodel techniques are recommended.

Index Terms— Product design, design optimization, haptic interface, multi-criteria, system requirement

I. INTRODUCTION

Haptics refers to the science of human touch. The original meaning of this word, “the active touch of real objects by humans” introduced in the field of experimental psychology, was redefined in the late 1980s to enlarge its scope to include machine touch and human-machine touch interactions [1]. Research on haptics can be divided into three subjects: human haptics, machine haptics, and computer haptics. Haptics refers to the study of human sensing and manipulation through touch; machine haptics refers to the design, construction and use of mechanical devices called haptic devices or haptic interfaces to replace or augment human touch; and computer haptics refers to software and algorithms used for generating and rendering collisions with virtual objects.

A haptic device is an actuated human-machine interface which measures the position and forces of the user that operates the device and provides force and torque feedback to the operator through the human sense of touch based on reacting forces and torques from objects in a real, tele-operated, or virtual environment [2]. As an emerging technology, haptic interfaces have been intensively explored with applications in the areas of rehabilitation robotics and prosthetics, surgical simulators and robotic-assisted surgery, virtual prototyping for industrial application, 3D modeling, computer gaming and others.

To evaluate the quality of a haptic device with force and torque feedback, a set of performance indices derived from the preliminary requirements have been proposed [3][4][5]. However, the performance requirements are usually multi-criteria and sometimes interacting or conflicting, e.g., large stiffness and small inertia, sufficient workspace and low weight, high functional performance, and low cost. Optimization is one of the main approaches to find an optimal design of a haptic device that satisfies all requirements by minimizing or maximizing some performance indices, defined as objective functions. Many researchers have used optimization approaches to search for the optimal haptic device design. However, predicting the performance of a haptic device, especially a high-performing haptic unit, usually involves computationally intensive simulations and analyses with complex and heterogeneous models.

In order to study what are the common design and performance requirements of haptic devices and what optimization approaches have been used to improve optimization effectiveness and efficiency, the following research questions are elaborated on in this paper:

1. What are the most commonly used performance indices for evaluating the quality of a haptic device?
2. What are the currently available haptic devices both on the market and in research labs?
3. What methods and combinations of methods are proposed in the literature for design optimization of haptic devices, including classification of the reported design tasks and the corresponding optimization
formulations (objective functions, design variables, and constraints) as well as the optimization algorithms that were used?

The literature search method used in this study is described in Section 2. The two first research questions are elaborated on in section 3, and research question three in section 4. The overall findings are discussed in Section 5. Section 6 provides answers to the three research questions, and section 7 gives recommendations for further application and implementation of methods that enable design optimization of high-performing haptic devices.

II. LITERATURE SEARCH

To answer the research questions, a systematic literature study on design optimization of (machine) haptic devices was performed. That is, research in the other two subjects of haptics, human haptics, and computer haptics, is not explicitly covered in the literature study. Haptic devices can be classified as either ground-based devices (linkage-based devices placed on the ground or a table) or exoskeletal force-reflecting haptic devices (gloves, suits, exoskeletal devices) [2]. The focus of this review is on ground-based devices. Hence the wearable haptic devices were not considered in the literature study. Furthermore, the presented study was conducted with a special focus on the mechanical design of haptic devices, and the physical performance criteria and methods used in mechanical design optimization of haptic devices.

A. Search Criteria

Design of the mechanism and the control system of haptic devices are the two main subjects that are researched. When designing a high-performing haptic device, it is crucial to spend sufficient effort specifying the design requirements. Some performance measures for a haptic device (e.g., the number of degrees-of-freedom) are mainly determined by the device mechanism. However, the control system can make contributions to the performance by controlling the actuators, i.e., the motors, in such a manner that some unfavorable or unstable performance, such as the friction or gravity, can be compensated. However, since our focus is on the mechanism design of haptic devices, the control system is not further studied here.

Since the invention of haptic devices, many commercial haptic devices have been realized. Desktop haptic devices, which can be placed on a table, are the major products found on the market. Over time, manufacturers of some of the devices have changed and/or merged, and some devices have been improved or are not for producing anymore. Hence, only the commercial haptic desktop devices which are currently available on the market, and with published detail product specifications, are considered in this study. Furthermore, development of novel haptic devices is a continuously ongoing activity in many research fields, and many new concepts and structures have been proposed. However, we only consider research on existing prototypes that have published a detail property description.

Our focus here is on multi-criteria design and optimization, that is multi-objective optimization cases. Consequently, literature that presents a case with a single objective is not treated here. Optimization of a haptic device involves four major aspects, the performance indices used as objectives or constraints, the design variables, the optimization formulation and the solution method, and the optimization algorithm used to search for optimal solutions. In order to have a comprehensive study of the optimization tasks and their solutions, only research and publications with detailed descriptions of these four aspects are treated.

B. Selection

The present review consists of two parts; the design and physical performance requirements of ground-based haptic devices, and multi-objective optimization of haptic devices. The physical performance requirements were found in published research papers. The search of commercial haptic devices was mainly made through the websites, which are accessible in 2017, of haptic device manufactures. The search for prototypes in research labs was based on both the websites of some identified labs as well as research papers published between 1998 and 2017. For the multi-objective optimization tasks of haptic devices, relevant papers published between 2006 and 2017 were studied.

In general, the IEEE Xplore [6], ELSEVIER[7], and Springer [8] databases were used as sources in this complementary study. Papers were searched according to all the different combinations of the selected keywords design/optimal design/optimization, and haptic device/haptic manipulator/haptic interface. The keywords, manipulators/robotic arms, were originally involved in the searching rule since these devices have similarities to haptic devices. However, since we found enough publications on haptic devices, and the performance requirements of manipulators and robotic arms showed some significant differences between haptic devices, the searching area was narrowed to haptic devices only.

III. DESIGN OF HAPTIC DEVICES

A. Performance Requirements

The haptic device, as a mechanical input/output (I/O) interface, tracks the user input, such as the position or force applied on one or more end effectors, and provides output, i.e., haptic feedback to the user based on the user interaction with objects in a virtual or tele-operated world. According to the type of haptic feedback provided by haptic devices, they can be divided into force-feedback devices and tactile-feedback devices. Force feedback devices address the sensations felt by the muscles, joints, and tendons [9]. Tactile-feedback devices, on the other hand, address the sensations felt by the skin, such as texture, temperature, and vibration. Based on the grounding location, haptic devices can also be classified as ground-based devices (such as joysticks, pen- and linkage-based desktop devices) or exoskeletal force-reflecting devices (wearable devices such as gloves, suits and exoskeletal devices) [2].
Although many haptic interfaces have emerged in the past 20 years, we will only discuss the ground-based haptic devices with force-feedback in our review.

The performance requirements are usually used to evaluate the most elemental electrical and mechanical properties of a haptic device. In prior work, researchers have categorized and listed the most relevant performance requirements [1][5][10][11]. In general, there are no typical values for these properties which typically depend on the specific application that is targeted. But, there seems to be a consensus on what these idealities are [12][13][14][5]. The meaning of the most commonly used performance requirements and their ideal qualitative values are presented in Table 1.

Since a haptic device is not only a manipulator but also a force-feedback device, the degrees-of-freedom for haptic devices is commonly classified as passive and active degrees-of-freedom (DOF). The passive DOF show the freedom of motion of the end-effector driven by the user, and the active DOF is the number of independent force/torque feedback directions that can be displayed by the device.

The workspace is classified as a reachable workspace or dexterous workspace. The reachable workspace includes the set points that can be reached by the end-effector, and the dexterous workspace consists of the points reached in arbitrary orientations. Mechanical singularities within the workspace should be forbidden, i.e., they put constraints on the workspace.

B. Commercial Haptic Devices and Research Prototypes

Haptic devices with force feedback are commonly classified as serial, parallel, or hybrid kinematic structures. Serial haptic devices have a serial kinematic structure, which consists of a single open-loop chain of links and joints that connect the end-effector to a fixed base. Parallel haptic devices have a closed-loop kinematic structure which connects the end-effector on the moving platform to a fixed-based, and the serial structure connects the end-effector to the parallel structure, which generates additional end-effector DOF. Compared to a serial structure, a parallel mechanism has potentially larger stiffness and bandwidth as well as higher accuracy and lower inertia but provides a smaller workspace. A hybrid mechanism may combine the advantages of the serial and parallel kinematic structures.

According to the descriptions and specifications of currently available commercial haptic interfaces and research prototypes in laboratory setup developed for different purposes and requirements [16][17], the most commonly listed properties are:

- The structure of the device,
- The number of degrees-of-freedom,
- Translational and rotational workspace,
- Peak and continuous force and/or torque,
- Stiffness,
- Position and/or force resolution,
- Bandwidth.

Table 2 and Table 3 list currently available commercial desktop haptic devices and prototypes in research labs, respectively. The five most common properties are shown in the table including the type of kinematic structure (the mechanism), the input and output (I/O) number of DOF, the dimensions of the translational and rotational workspace, the peak force and/or torque that can be applied on the device end-effector, and the structure stiffness. Only devices or prototypes stating at least three of these properties have been considered.

Browsing the specifications of the haptic devices listed in the tables above, indicate that manufacturers and researchers tend to develop and research stiff haptic devices with a large number of DOF and a large workspace, and the ability to exert high fidelity forces and torques. Most of the force feedback devices are equipped with generic end effectors, such as pens, balls, and tubes. But some devices use modified end effectors, such as scissors (Freedom 6S [18]), gloves (CyberForce [19])

<table>
<thead>
<tr>
<th>Performance criterion</th>
<th>Qualitative Ideal</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees-of-freedom</td>
<td>↑</td>
<td>The number of orthogonal motions either permitted or driven by the device</td>
</tr>
<tr>
<td>Workspace</td>
<td>↑</td>
<td>The area or volume in real-world space that the end-effector can reach</td>
</tr>
<tr>
<td>Isotropy</td>
<td>↑</td>
<td>The uniformity of the end-effector moving in all generalized workspace directions</td>
</tr>
<tr>
<td>Dexterity/ Manipulability</td>
<td>↑</td>
<td>Quantification of the device’s ease of arbitrarily changing position and orientation for a given posture</td>
</tr>
<tr>
<td>Inertia</td>
<td>↓</td>
<td>The resistance felt by the user while moving the end-effector</td>
</tr>
<tr>
<td>Friction</td>
<td>↓</td>
<td>Forces of resistance that oppose motion</td>
</tr>
<tr>
<td>Stiffness</td>
<td>↑</td>
<td>The ability of a device to mimic a solid virtual wall or object</td>
</tr>
<tr>
<td>Input position resolution</td>
<td>↑</td>
<td>The smallest change of position which can be detected by sensors</td>
</tr>
<tr>
<td>Output force resolution</td>
<td>↑</td>
<td>The smallest incremental force that can be generated by the device</td>
</tr>
<tr>
<td>Operating bandwidth</td>
<td>↑</td>
<td>The speed of response to a given excitation</td>
</tr>
<tr>
<td>Peak force</td>
<td>↑</td>
<td>The maximum force that the actuators of a device can generate over a very small time interval</td>
</tr>
<tr>
<td>Continuous force</td>
<td>↑</td>
<td>The force that the end-effector can exert for an extended period</td>
</tr>
<tr>
<td>Peak acceleration</td>
<td>↑</td>
<td>The ability of a device to simulate the impact with stiff virtual objects</td>
</tr>
</tbody>
</table>

↑: large/high value of the index is required, ↓: low value of the index is required
and tools, to extend the usage and the device DOF. To provide extra degrees of force feedback for a particular task, there are also some examples that combine two commercial haptic devices, for example, the SimQuest’s burr hole surgical simulator [20] which is a combination of two Falcon [21] haptic devices, and the Delthaptic [22], which combines two Delta haptic devices through a handle.

Furthermore, for a specific purpose, such as haptic-based virtual assembly simulation, serval commercial devices and prototypes have been developed to extend haptic force feedback to a larger workspace. Large-scale cable-driven haptic devices, such as the iFell6-BH1500 [23] and Inca™ 6D [24], have been developed for virtual assembly usages. Due to their structure with several cable-driving modules mounted on a large frame, they can provide a large workspace, higher stiffness, and lower back driving force compared to the well-known commercial haptic device Phantom Premium 3.0. Furthermore, many researchers have developed other large-scale haptic devices by adding additional redundant axes to the ground-based haptic devices [25] or mounted a haptic device on a mobile robot [26]. By an additional connection to other robots or devices, the reachable volume can be extended to function in a full-scale virtual environment.

### Table 2. Commercial Force-feedback and Ground-based Desktop Haptic Devices

<table>
<thead>
<tr>
<th>Company</th>
<th>Device</th>
<th>Mechanism</th>
<th>DOF</th>
<th>Workspace Translation[mm]/Rotation[deg]</th>
<th>Peak Force[N]/Torque[Nmm]</th>
<th>Stiffness [N/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D SYSTEMS Geomagic® [16]</td>
<td>Touch</td>
<td>Serial</td>
<td>6/3</td>
<td>160x120x70/254x178x127/381x267x191/335x260x297</td>
<td>3.3/0</td>
<td>1.02~2.31</td>
</tr>
<tr>
<td></td>
<td>Touch X</td>
<td>Serial</td>
<td>6/6</td>
<td>160x120x120/254x178x127/381x267x191/335x260x297</td>
<td>7.9/0</td>
<td>1.48~2.35</td>
</tr>
<tr>
<td></td>
<td>Phantom® Premium 1.0</td>
<td>Hybrid</td>
<td></td>
<td>838x584x406/335x260x297</td>
<td>8.5/170-515</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Premium 1.5</td>
<td>Hybrid</td>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Premium 3.0</td>
<td>Hybrid</td>
<td></td>
<td></td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td>Force Dimension [27]</td>
<td>omega.3</td>
<td>Parallel</td>
<td>3/3</td>
<td>Ø 160x110/Ø160x110</td>
<td>12/0</td>
<td>14.5</td>
</tr>
<tr>
<td></td>
<td>omega.6</td>
<td>Hybrid</td>
<td>6/3</td>
<td>Ø 240x140x320</td>
<td>12/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>omega.7</td>
<td>Hybrid</td>
<td>7/3</td>
<td>Ø 400x260/Ø 400x260/Ø 400x260/±20</td>
<td>12/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>delta.3</td>
<td>Hybrid</td>
<td>3/3</td>
<td>Ø 190x130/230</td>
<td>12/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>delta.6</td>
<td>Hybrid</td>
<td>6/6</td>
<td>Ø 230x140x200</td>
<td>12/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>sigma.7</td>
<td>Hybrid</td>
<td>7**/6</td>
<td>Ø 838x584x406/335x260x297</td>
<td>12/0</td>
<td></td>
</tr>
<tr>
<td>Novint [21]</td>
<td>Falcon®</td>
<td>Parallel</td>
<td>3/3</td>
<td>~Ø100x100x100</td>
<td>10/0</td>
<td></td>
</tr>
<tr>
<td>Haption [28]</td>
<td>Virtuose 3D Desktop</td>
<td>Serial</td>
<td>6/3</td>
<td>200x200x200/145x115x148</td>
<td>10/0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Virtuose 6D Desktop</td>
<td>Serial</td>
<td>6/6</td>
<td>200x200x200/200x90x200</td>
<td>10/400</td>
<td></td>
</tr>
<tr>
<td>Quanser [29]</td>
<td>HD2</td>
<td>Parallel</td>
<td>6/6</td>
<td>800x350x350/180x180</td>
<td>13.94–19.71/1720</td>
<td></td>
</tr>
<tr>
<td>MPB Technologies Inc. [18]</td>
<td>Freedom 6S</td>
<td>Serial</td>
<td>6</td>
<td>170x220x330/340x170x230</td>
<td>2.5/150-370</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Freedom 7S</td>
<td>Serial</td>
<td>7**/6</td>
<td>Ø 170x220x330/340x170x230</td>
<td>2.5/150-370</td>
<td></td>
</tr>
<tr>
<td>CyberGlove Systems [19]</td>
<td>CyberForce</td>
<td>Serial</td>
<td>6/3</td>
<td>~Ø335x305x305</td>
<td>8.8/0</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3. Ground-based Research Prototype with Force Feedback and Linkage Connection

<table>
<thead>
<tr>
<th>University/Institute</th>
<th>Device</th>
<th>Mechanism</th>
<th>DOF</th>
<th>Workspace Translation[mm]/Rotation[deg]</th>
<th>Peak Force[N]/Torque[Nmm]</th>
<th>Stiffness [N/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Tsukuba [30]</td>
<td>Haptic Master</td>
<td>Parallel</td>
<td>6/6</td>
<td>Sphere Ø400</td>
<td>~20.6/549</td>
<td>~0.28</td>
</tr>
<tr>
<td>CEIT [31]</td>
<td>LHIFAM</td>
<td>Serial</td>
<td>6/3</td>
<td>Ø1110x1500</td>
<td>42.5–72/0</td>
<td>NA</td>
</tr>
<tr>
<td>Northwestern University [33]</td>
<td>Cobotic Hand Controller</td>
<td>Parallel</td>
<td>6/6</td>
<td>NA/22–25</td>
<td>50/NA</td>
<td>20–400</td>
</tr>
<tr>
<td>CEA-LIST [34]</td>
<td>CAD like Desktop</td>
<td>Parallel</td>
<td>6/6</td>
<td>150x150x150/±45</td>
<td>20/500</td>
<td>NA</td>
</tr>
<tr>
<td>University of Colorado [35]</td>
<td>CU HI</td>
<td>Parallel</td>
<td>5/5</td>
<td>Sphere Ø300</td>
<td>8/NA</td>
<td>NA</td>
</tr>
<tr>
<td>KTH Royal Institute of Technology [36]</td>
<td>Ares</td>
<td>Parallel</td>
<td>6/6</td>
<td>75x75x100/±45</td>
<td>54/1200</td>
<td>60</td>
</tr>
<tr>
<td>KTH Royal Institute of Technology [37]</td>
<td>TAU</td>
<td>Parallel</td>
<td>6/6</td>
<td>70x80x100/±45</td>
<td>48–62/1200</td>
<td>55–70</td>
</tr>
<tr>
<td>Tohoku University [38]</td>
<td>Compact 6-DOF</td>
<td>Hybrid</td>
<td>6/6</td>
<td>Sphere Ø150/±70</td>
<td>10/NA</td>
<td>NA</td>
</tr>
<tr>
<td>Nagoya Institute of Technology [17]</td>
<td>DELTA-4</td>
<td>Hybrid</td>
<td>6/3</td>
<td>Ø500x120/±80</td>
<td>50/0</td>
<td>NA</td>
</tr>
</tbody>
</table>

(NA) Not available from the source.
The design task to develop a haptic device is usually multi-criteria, that is, more than one performance criterion needs to be satisfied. In order to efficiently and effectively develop a haptic device that satisfies all performance requirements, the multi-objective optimization (MOO) is usually used to find the optimal design which is quantified by the required performance indices.

An optimization problem containing \( n \) objective functions is formulated as:

\[
\begin{align*}
\text{minimize} & \quad f_1(x), f_2(x), \ldots, f_n(x) \\
\text{subject to} & \quad g(x) \leq 0 \\
& \quad h(x) = 0 \\
& \quad x_{\text{lower}} \leq x \leq x_{\text{upper}}
\end{align*}
\]

The optimization goal is to find the values of the design variables \( x \) that minimize the \( n \) objective functions \( f_{l(a,n)} \) and satisfies both the inequality and equality constraints \( g \) and \( h \). The design variables can be continuous or discrete, and they must be kept within the upper and lower limits called \( x_{\text{upper}} \) and \( x_{\text{lower}} \).

Classical approaches to address/formulate an MOO problem are to change it to a single objective problem by weighting each objective function and summing them as a single objective function (the weighted-sum approach, WS), or by prioritizing one objective and constraining less important objective functions [39]. The weighting coefficients are used to reflect the relative importance of the original objective functions. As a result, only one optimal solution can be found after completing the entire optimization process. The drawback of these approaches is that the apriori preferences or weights of the objectives, which might be subjective or biased, are assumed before optimization. An alternative approach is to incorporate all optimization criteria within the optimization process and address them simultaneously to find a set of optimal solutions. The set of optimal solutions constitutes the Pareto-front (PF) [40] which is consequently a curve, a surface, or a hypersurface for the respective cases of two, three or more objectives. The Pareto-front approach provides a better understanding of the optimization problem and allows the designers to make an informed decision from a wide range of optimal solutions. The drawback of this approach is that it might consume a significant amount of computational resources.

To improve a design with multi-criteria and sometimes multidisciplinary performance requirements, an optimization approach referred to as multidisciplinary design optimization (MDO) has been developed. The MDO has primarily been used for aerospace applications [41][42][43], and further extended to other engineering systems, such as bridges [44], buildings [45], railways vehicles [46], turbines [47], automotive vehicle [48], robotics [49], etc. The advantage of MDO is that it cannot only decompose a complex problem into sub-problems, which allows parallel analyses and optimization but also consider the interactions between the sub-problems or disciplines in the design process. By solving the MDO problem in the early design phase and taking advantage of advanced computational analysis tools, designers can simultaneously improve the design and also potentially reduce the time and cost of the design cycle.

Due to the nonlinear, large-scale nature of mechanisms and non-convex properties of performance indices with respect to the design variables, it is a challenge to find an optimum haptic device design. Many optimization approaches and methods have been proposed to solve such kind of optimization problems. The evolutionary algorithms (EAs) [50] is considered as a well-suited optimization algorithm for the described multi-objective optimization problem. In general, evolutionary algorithms are divided into genetic algorithms (GAs), evolution strategies (ESs), and evolutionary programming (EP) [51]. Among these algorithms, the multi-objective genetic algorithm (MOGA) [52] and non-dominant sorted genetic algorithm (NSGA-II) [53] have been widely used for multi-criteria optimization of robotic structures and parallel kinematic manipulators [54][55][56][49].

Table 4 lists some multi-objective design optimization cases of haptic devices published in the literature. The optimization task, including defining objectives, design variables and constraints, as well as the formulation/solving approach (such as the Pareto-front approach or weighted-sum approach) and used optimization algorithm (for example, the Genetic Algorithms) are listed for each referred paper, respectively. The number of design variables is stated together with their types.

As shown in Table 4, the most used design variables are mechanical parameters (MPs), such as arm lengths or platform diameter. Different performance criteria were defined as objectives, including kinematic and dynamic performance. In the list of objectives, force/torque capacity stands for the maximal force/torque that can be applied on the end effector of the device. Geometric limits (such as the movable range of the joints), singularity, prescribed workspace, and the maximum force applied by the user, are used to constrain the design. The generic algorithms are most commonly used to find the optimal solutions. But, some cases used the culling algorithm [57] which identifies non-optimal parameters and culls them from the search space until only the optimum remains. Both the Pareto-front (PF) approach and the weighted-sum (WS) approach are used to solve the optimization problems. The MDO approach was used by Sun et al. [58] together with the Pareto-front approach to solving the MOO haptic device optimization problem. Furthermore, in order to assure that all design indices were equally active in the optimization process for cases using the weighted-sum approach, the objective function was defined using normalized performance indices [59], as given in (2).

\[
\bar{PI} = \frac{PI - PI_{\text{min}}}{PI_{\text{max}} - PI_{\text{min}}} \tag{2}
\]

where \( \bar{PI} \) is the normalized performance index, \( PI_{\text{min}} \) and \( PI_{\text{max}} \) are the minimum and maximum values of the performance index for the design parameters of any design in the optimization.
In most cases, the value of the performance index is calculated with numerical equations. But recent researchers seem to evaluate the value of the performance indices using geometric-based models, such as measuring the weight of the device with the geometric models [60], using FE models to evaluate the structural stiffness [61] or strength [49], and using dynamic system models to analyze the dynamic isotropy [58] or the required actuator force [62].

In general, the computational resources required to analyze the performance indices increase with the complexity of the device structure as well as with the increased level of detail in the design phase. For design cases with a complex structure and/or with a detailed design, metamodels [73] have been used to replace the computationally intensive system model in the optimization process [58]. A metamodel is a surrogate model of the “full” system model, and it is created by a mathematical description based on a dataset of input and the corresponding output from the system model. This approach has been shown to be an effective approach for engineering design in many fields, such as aerospace systems [74], aerodynamics [75], automotive systems [76][77][78], robots [79], etc. The advantage of this approach is that it can decrease the computational time for evaluating simulation models, and also to enable parallel simulation and potentially providing better solutions using advanced optimization algorithms with a large amount of evaluations. The main drawback of the metamodel approach is that it introduces an additional source of error into the optimization process. Hence, it is important to have an accurate enough metamodel of the system model and a metamodel that require “acceptable” computational resources.

V. DISCUSSION

In this paper, in order to have the overall idea about how a haptic device could be designed, the physical performance specifications of high-performing haptic devices found in the literature were listed first. Several haptic devices available on...
the market and in research labs were presented as a table, including the most commonly described properties, such as the structure, number of degrees-of-freedom, workspace, peak force provided by the device and the stiffness.

It is clear that the haptic device should satisfy multiple performance requirements simultaneously based on its targeted application. In order to find an optimal design that can satisfy all requirements, the multi-objective optimization method is used by many researchers. Two commonly used methods to solve the problem are the weighted-sum approach and the Pareto-front approach. The weighted-sum approach transfers the multi-objective problem into a single objective problem which simplifies the optimization task but needs apriori or existing knowledge of the system. On the other hand, the Pareto-front approach treats all optimization criteria simultaneously and postpones decision making after having a more thorough knowledge of the system and its performance.

The optimization purpose is to find the optimal solution(s) for the multi-criteria design cases with reasonable efficiency. In most cases, the value of a performance index is calculated with numerical equations. But an observed trend is that more researchers now evaluate the values of the performance indices using geometry-based models, such as the CAD, FE and dynamic system models. With the increasing level of detail in the design model, the required computational resources are exponentially increasing. For such cases, it is significant to find a more efficient method to solve the optimization problems.

VI. CONCLUSIONS

For design and evaluating the performance of a haptic device, some commonly used performance requirements were found from product specifications of existing haptic devices, such as the number of degrees-of-freedom, dynamic inertia, kinematic isotropy, stiffness, peak and continuous force, position/force resolution, bandwidth, etc. Based on the listed commercial haptic devices and prototypes, parallel and hybrid kinematic structures are more commonly used than serial structures.

Different performance indices to quantify the performance specifications of haptic devices have been proposed. To have a high-performing haptic device, many performance indices need to be satisfied simultaneously. The multi-objective optimization (MOO) method is one approach to search for an optimal design which can satisfy all requirements. Based on the listed MOO cases of haptic devices found in literature, the most common optimization tasks are to maximize workspace, kinematic isotropy, as well as the peak force/torque provided by the device, and to minimize the dynamic inertia, while satisfying the prescribed workspace and avoiding singularity and exceeding the geometric limits constrained by the joints. The number of design variables various from 2 to 9, and the most commonly used design variables are mechanical parameters, including the lengths and diameters of the mechanical components.

To solve the MOO problem, both the weighted-sum approach and Pareto-front approach are used to formulate the optimization problem. In some cases, the MDO and metamodeling approaches were utilized to increase the efficiency of the optimization process. Furthermore, the genetic algorithm is commonly used in searching the optimal solutions in the design space.

VII. RECOMMENDATIONS

To formulate and solve the multi-objective problems of haptic devices, the weighted-sum approach and the Pareto-front approach are mostly used. However, the selection of the most efficient and effective solution methods is case-dependent. The weighted-sum approach is more suitable for cases where the system and the preference of the performance criteria are known and fixed. When there is no or very limited knowledge of the system, and the design task is unclear, the Pareto-front approach is recommended.

Furthermore, for complex design cases with many and sometimes highly coupled performance criteria, the multidisciplinary design optimization (MDO) method could decouple the complex problem and enable parallel analysis and optimization, and hence potentially increase the efficiency of the optimization process. In terms of having a complex kinematic structure (e.g., the hybrid kinematic structure) or computational exhaustive detail models, simulations or analyses to evaluate the performance criteria, it is recommended to use the metamodel technique. To replace the “full” system model by the metamodel can significantly increase the efficiency of the optimization process with an acceptable accuracy of the found optimal solution.

REFERENCES


