Measurement and Optimization of Minimally Invasive Intervention Device Design Fitness Using a Multiobjective Weighted Isotropy Index

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The recent transition from multiple-port to single-port systems in minimally invasive intervention (MII) procedures has created a need for more flexible, dexterous robotic manipulation devices capable of spanning an entire surgical workspace without the risk of collateral damage. The design of such devices requires a careful balance of the mechanical complexity needed to facilitate clinical functionality and the cost of manufacturing and operating the device. This paper presents a novel metric for measuring the design fitness of kinematically redundant robotic MII devices and for optimizing them to achieve that balance. The proposed fitness metric rewards designs that are conducive to collision avoidance and energy conservation while penalizing those with exorbitant design complexities that adversely affect the economic feasibility of an MII system. The authors’ metric is used here to design a kinematically redundant, single-port MII device capable of accessing the cardiothoracic cavity through a single subxiphoid port and reaching several regions of interest, consistent with procedures such as epicardial ablation and therapeutic substance injection, with minimal physiologic disturbance. The design of this device is determined by a morphological optimization process, which searches a discrete mechanical design parameter space, consisting of linkage parts, part dimensions, and actuator types, using genetic algorithms. The execution of specific surgical maneuvers is simulated for each candidate MII device design, and the design is improved until the fitness metric is maximized. The results of this optimization study demonstrate that redesigning a 20 degree-of-freedom (DOF) MII device using the proposed metric decreased the DOF in the design by 45% while ensuring near-optimal levels of kinematic flexibility. The results also demonstrate the ability of the fitness metric to elucidate the relationship between functionality and complexity and to produce suitable device designs over a broad range of performance and cost goals. The authors conclude that this new design fitness metric, while heuristic in nature, holds the potential to improve both the clinical value and the economy of a wide variety of single-port MII devices, including those used in cardiothoracic surgery. [DOI: 10.1115/1.4001107]

1 Introduction

The task of designing minimally invasive intervention (MII) devices, also known as minimally invasive surgery (MIS) devices, is an important and challenging one given the elaborate nature of the procedures for which they are used, the precision and dexterity required by those procedures, and the many morphological and mechanical design factors that they entail. As MII platforms progress from conventional, rigid multiple-port systems toward more compact and flexible single-port systems, the relationship between device design complexity and clinical function becomes more sensitive and the economic implications more severe and prohibitive. This paper focuses on the measurement of the relationship between robotic MII device design cost and clinical functionality using a novel design fitness metric. This fitness metric takes into account design factors such as morphological structure and dimension, the number of degrees of freedom (DOFs) comprising a robotic MII device linkage, and the actuation mechanisms that power the MII device, all of which contribute to the mechanical and economic feasibilities of a device. This fitness metric also measures kinematic dexterity, collision-avoidance capability, and energy consumption, all of which indicate the quality of MII device performance on particular interventional maneuvers. The proposed metric is used to optimize the design of a highly articulated, single-port robotic MII device used for cardiothoracic interventions, an area of surgery for which single-port devices hold significant potential. Through several optimization experiments, the proposed metric is shown to yield designs that improve the clinical value and versatility of the cardiothoracic MII device while mitigating its design cost.

Since the endeavor to develop advanced surgical devices began in the early 1990s, the field of robot assisted surgery has seen myriad technological advances that have served to improve clinical outcomes in MII [1,2]. Robotic MII devices are widely recognized for their precision and robustness, their ability to minimize the risk of infection, and for their capacity to incorporate advanced imaging and biosensing devices. MII devices have led to significantly shorter hospital stays and recovery times than those possible with conventional open-surgery or manual MIS [3], and have been used successfully in fields such as biopsy [4], urology [5], and cardiothoracic surgery [6].

Many of the earliest and most well-recognized MII devices, including the ZEUS® (Computer Motion Inc., Goleta, CA) and the DA VINCI® (Intuitive Surgical Inc., Sunnyvale, CA), are multiple-
port systems that have several robotic arms. These systems have proven to be adept at performing procedures requiring precise, simultaneous use of several surgical tools such as endoscopic cameras, cauteries, and forceps. Despite the success of multiple-port MII systems in decreasing infection risk and recovery time, these systems have suffered from both economic and functional drawbacks. Economically, multiple-port systems are difficult and expensive to construct and usually entail high maintenance costs. Functionally, multiple-port systems, due to sheer size and complexity, require considerable training and long pre-operative preparation times, and are limited in their portability. Because they typically use kinematically rigid tools, multiple-port systems are also unsuitable for geometrically complex surgical workspaces where the threat of undesired anatomical contact necessitates preparatory surgical procedures and drug administration that can lead to serious, possibly fatal physiological disturbances. The complex MII procedures that are tractable with multiple-port systems can require as many as seven ports to reach all surgical areas of interest, negating some of the advantages MII has over open-surgery (Fig. 1). For these reasons, MII device research has taken a departure from multiple-port applications and focused on highly articulated devices that hold the potential to mitigate, if not eliminate, many of these functional and economic issues.

Highly articulated, kinematically redundant MII devices afford surgeons the same dexterity and range of motion as multiple-port systems while using only a single incision. These single-port devices hold the promise of facilitating procedures in small, geometrically complex spaces, such as those seen in cardiothoracic surgery, with even lower risks of infection and patient discomfort than possible with multiple-port systems. Single-port MII devices recently developed for interpericardial intervention [7], laparoscopic surgery [8], ocular surgery [9], and gastrointestinal interventions [10,11] have demonstrated the capacity to facilitate complex MII procedures while yielding clinical efficacy comparable to that seen with open-surgery or manual multiple-port MIS.

Many single-port MII solutions employ kinematically redundant structures. These structures, which have more DOFs than necessary to span a surgical workspace, can greatly reduce the incidence of physiological disturbances by increasing collision-avoidance capability, and can also reduce the amount of actuation energy required by facilitating energy-efficient motion planning. The degree of collision-avoidance capability is highly dependent upon morphological design and can be significantly improved using the proper design methodology and control schemes. However, the compulsory sophistication of kinematic devices requires careful consideration of morphological and mechanical design to ensure that the complexity and cost of design are not economically prohibitive enough to outweigh the clinical benefits of improved device flexibility.

The primary contribution of this paper is a design fitness metric, which has been developed to simultaneously measure the design complexity and task performance of MII devices. This metric, based upon the multiobjective weighted global isotropy index (MWGII) [12], quantifies an MII devices capacity to avoid collisions with motion impediments and to minimize the mechanical torque required for the intended task, while also considering design factors such as part selection and design complexity, which heavily influence economic feasibility of a MII system. The proposed fitness metric is used to design a kinematically redundant robotic MII device capable of facilitating single-port cardiothoracic interventions with minimal physiologic disturbance. Section 2 explains the clinical relevance of designing a kinematically redundant MII device suited for cardiothoracic procedures. Section 3 reviews previous work on kinematic modeling and manipulator design, and describes the formulation of the proposed design fitness metric and its physical meaning. Section 4 details the methods, context, and setup of the MII device design optimization experiments, which are based upon the authors’ proposed fitness metric. Section 5 presents the results of the optimization experiments and makes observations on the cogency and utility of the proposed metric, and Sec. 6 discusses the implications of these results for the future of MII and other kinematically redundant device designs.

2 Clinical Relevance

Notwithstanding the historical success of conventional open-heart surgical procedures, the use of MII devices is steadily gaining traction as a viable and perhaps superior alternative for the treatment of cardiovascular disease [13]. Much of the increased focus on MII in cardiothoracic procedures stems from its potential to obviate the morbidity associated with cardiopulmonary bypasses (CPBs) and median sternotomies. Traction is particularly strong for applications in intrapericardial therapeutic substance delivery [14,15], epicardial electrode placement [16], and gene therapy [17], where surgery can be relegated to the pericardium.

Most minimally invasive cardiac interventions to date have been performed using multiple-port systems whose kinematically rigid tools provide limited range and dexterity despite the number of ports used. This rigidity necessitates transthoracic port access, which typically requires invasion of the pleural space and induced lung deflation to reach the pericardium. The transthoracic approach, while effective and less invasive than open-surgery, entails the risk of collateral damage and complications such as fibrillation caused by inadvertent cardiac compression (unpublished observations). To prevent these complications, a less-invasive single subxiphoid transpericardial port can be used (Fig. 2). This approach, however, requires the use of highly articulated, single-port MII devices to negotiate the anatomical structures between the access port and the heart.

Previous studies on the development of highly articulated single-port MII devices have produced a wide variety of solutions,
from continuous multibackbone devices [18] and mobile crawling devices [19] to rigid-body linkages [9,10]. Among these previous works, the ones most relevant to our solution are rigid-body linkages. Most rigid-body solutions, including the aforementioned ones, are nonredundant solutions suited for less complex MII procedures that involve few motion impediments and relatively simple tool tip motions. The minimally invasive cardiac interventions addressed in the paper require a kinematically redundant device capable of higher degrees of dexterity and greater flexibility for collision avoidance. Consequently, this device also entails greater mechanical sophistication and, by extension, greater design complexity that must be mitigated to ensure that the solution is economical.

This study focuses on the use of the proposed fitness metric to optimize the design of a rigid-body, kinematically redundant MII device for use in subxiphoid pericardial interventions. The MII device must access the cardiothoracic cavity through a 12 mm subxiphoid port, negotiate the pleural space and surrounding anatomical structures, as shown in Fig. 3, and reach the aortic arch and transverse sinus, tomical structures, as shown in Fig. 3, and reach the aortic arch

The major MII motion impediments within the cardiothoracic cavity are the lungs, ribs, and heart, and to accommodate the limitations of our simulation software, that motion in the cavity due to the beating of the heart is negligible.

3 Measurement of Device Design Quality

3.1 Previous Manipulator Fitness Metrics. The quality of a manipulator’s design and performance is typically measured by its kinematic dexterity, which is defined as the ability of a kinematic linkage to impart smooth, precise motion at manipulator end-effector. Several metrics have been developed to quantify kinematic dexterity, and many of these metrics are based on the manipulator Jacobian matrix $\mathbf{J}(\theta)$ [21,22], which for an nDOF serial manipulator maps an $n \times 1$ joint rate vector $\dot{\mathbf{\theta}}$ to a $6 \times 1$ end-effector velocity vector $\mathbf{x}$, Eq. (1). These metrics vary substantially in formulation, physical meaning, and range of application

$$J(\theta) \dot{\theta} = \mathbf{x}$$

One of the earliest Jacobian-based manipulator dexterity metrics, proposed by Yoshikawa [23], is the scalar manipulability index $\mu$, shown in Eq. (2)

$$\mu = \frac{\det(\mathbf{J}(\theta))}{\text{det}^{1/2}(\mathbf{J}(\theta) \mathbf{J}(\theta)^T)}$$

This index quantifies the potential speed and directionality of end-effector motion as a function of an instantaneous joint angle set $\theta$. This speed and directionality can be represented graphically using the manipulability ellipsoid. The manipulability index has great utility when measuring kinematic performance relative to a particular manipulator morphology in a specified configuration. However, when considering multiple design solutions, the manipulability index suffers from scale, order, and dimension homogeneity dependencies that prevent an accurate comparison of design and performance qualities between two or more competing morphologies.

Kim and Khosla [24] defined a measure of isotropy $\Delta$, which eliminates both scale and order dependency from dexterity measurement. This is done by taking the ratio of the arithmetic eigenvalue mean $\Psi$, and the order-independent manipulability, or geometric mean $M$ (Eq. (3)), which essentially quantifies the evenness of end-effector motion or the roundness of the manipulability ellipsoid

$$\Delta = \frac{M}{\Psi} = \frac{\sqrt[n]{\det(\mathbf{J}(\theta)\mathbf{J}(\theta)^T)}}{\text{trace}(\mathbf{J}(\theta)\mathbf{J}(\theta)^T)}$$

This measure is well-suited to optimization because of its scale independency but can only be used locally for a specific end-effector position. Stocco et al. [25] proposed a more comprehensive measure called the global isotropy index (GII), which takes the ratio of the smallest and largest singular values, or joint transmission rates, $\sigma_{\text{min}}$ and $\sigma_{\text{max}}$ of the manipulator Jacobian matrix over an entire motion path or workspace $W_{\text{space}}$ (Eq. (4)). Here, $x$ is the manipulator end-effector position and $p$ is the robot base location within the workspace

$$\text{GII}(p) = \max_{x \in W_{\text{space}}} \min_{\mathbf{\theta}} \sigma_{\text{min}}(\mathbf{J}(\theta,x))$$

The GII provides global dexterity measurement across an entire motion path or set of paths and is well-suited for optimization. It does not, however, consider collision avoidance and dynamic actuation limits, which are important for the design of kinematically redundant MII devices.

3.2 Weighted Isotropy Metric Formulation. Isotropy measures can be modified by using weighting matrices to reflect the impact that redundancy resolution, the utilization of redundant DOFs for secondary manipulation goals, has on end-effector mo-
tion. Recently, Hammond and Shimada [26] proposed the modification of the GII to account for the motion limits imposed by workspace obstacles by scaling the manipulator Jacobian with an $n \times n$ diagonal weighting matrix $W$, defined here

$$W(\theta, \xi) = \begin{bmatrix} w_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & w_n \end{bmatrix}$$ (5)

This matrix factors the effect of physical motion impediments into the isotropy measure by penalizing joint transmission rates when, and only when, joint motion causes movement toward undesired contact with the environment. Each diagonal element $w_i$ in matrix $W$, defined here

$$w_i = a[(1 - \beta)(1 + e^{\alpha(\theta_i - \theta_i^0)}) + \beta]$$ (6)

is a sigmoidal function of instantaneous kinematic joint velocity $\theta_i$, due to task trajectory goals, and a joint-space obstacle avoidance velocity $\xi_i$, where the subscript $i$ denotes the joint number. Variable $a$ is a proximity factor that decreases from 1 to 0 as minimum obstacle distance falls below some critical value, and $\beta$ is a value between 1 and 0 that limits the magnitude of isotropy penalty incurred for motion impedances. Figure 5 illustrates the change in manipulability that occurs when collision-avoidance penalties are incorporated into isotropy.

The GII, when weighted by matrix $W$, becomes the avoidance-weighted global isotropy index (AWGII) defined in Eq. (7). When obstacle-related motion penalties are not incurred, the weighted matrix becomes the identity matrix and the resulting singular value ratio is identical to the one obtained using the GII calculation, Eq. (4)

$$AWGII = \max_{\theta \in W_{\text{space}}} \min_{\xi} \frac{\sqrt{\sigma_{\min}(J(\theta)W(\theta, \xi)J(\theta)^T)}}{\sqrt{\sigma_{\min}(J(\theta)W(\theta, \xi)J(\theta)^T)}}$$ (7)

The joint-space obstacle avoidance velocities $\xi_i$ [27] used in forming the weight matrix are calculated by mapping task-space avoidance vectors onto the kinematic null space, using Eq. (8)

$$\dot{\theta} = J^s \dot{x} + \sum_{i=1}^{n} (\alpha_{g_i}[J_{o_i}(I - J_{e_i}J_{o_i}^T)](\alpha_{g_i}x_{o_i} - J_{e_i}x_e))$$ (8)

Here, $J_e$ is the end-effector Jacobian, $J_{o_i}$ is the obstacle point Jacobian for the $i$th obstacle, $x_{o_i}$ is the task-space avoidance velocity, $x_e$ is the end-effector velocity, and $\alpha_g$ and $\alpha_{o_i}$ are the gain term and the avoidance velocity magnitude for the $i$th obstacle, respectively.

Hammond and Shimada [28] also proposed the modification of the GII to account for joint torque limits by the same technique that is used for obstacle avoidance, only now an $n \times n$ diagonal torque-weighting matrix $T$, defined in Eq. (9), is employed

$$T(\tau, \tau_{\text{max}}) = \begin{bmatrix} t_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & t_n \end{bmatrix}$$ (9)

This matrix decreases the transmission of joint velocities to task-space velocities if joint motion results in excessive torque. Each element $t_i$ in matrix $T$, defined here

$$t_i = 1 - \lambda^{-W(\tau_i, \tau_{\text{max}})}}$$ (10)

is a nonlinear function of the instantaneous joint torque $\tau_i$ and maximum torque rating $\tau_{\text{max}}$. Variable $\lambda$ is an arbitrary scalar value between 0 and 1, which determines the maximum joint transmission penalty incurred when joint torque $\tau_i$ approaches $\tau_{\text{max}}$, while $\eta$ determines the function curvature, or rate of penalty increase.

The weights $t_i$ in matrix $T$ are exponentially proportional to the distance of joint torque $\tau_i$ from maximum joint torque $\tau_{\text{max}}$ also called the torque clearance. This relationship penalizes all motions that require torques near or beyond safety limits, and by extension, penalizes all manipulator morphologies or placements, which lead to these motions. The torque-weighted global isotropy index $TWGII$ is defined in Eq. (11)

$$TWGII = \max_{\theta \in W_{\text{space}}} \min_{\xi} \frac{\sqrt{\sigma_{\min}(J(\theta)T(\tau, \tau_{\text{max}})J(\theta)^T)}}{\sqrt{\sigma_{\min}(J(\theta)T(\tau, \tau_{\text{max}})J(\theta)^T)}}$$ (11)

When the torque-weighting matrix is the identity matrix, which is the case when no torque-related motion penalties are incurred, this ratio is identical to the one obtained using Eq. (4). Figure 6 illustrates the change in manipulability that occurs when torque penalties are incorporated into isotropy.

The joint torques used in the formulation of the torque-weighting matrix $T$ are calculated with the recursive Newton–Euler method [29]. The fundamental Newton–Euler method equation, shown here

$$\tau = H(\theta)\dot{\theta} + C(\theta) + g + F$$ (12)

consists of an inertia-matrix $H$, a Coriolis-centrifugal force vector $C$, and gravitational and external force vectors $g$ and $F$, respectively. Matrix $H$ is a function of joint position, and vector $C$ is a function of joint position and joint velocity. Both matrices play important roles not only in this formulation, but also in the calculation of energy consumption and in the motion control methods that minimize local torque requirements.

To consider both collision avoidance and torque minimization for the design of a kinematically redundant MII device, we take the product of the obstacle avoidance-weighting matrix $W$ and torque-weighting matrix $T$ to create a multiobjective weighting matrix $M$, as shown in Eq. (13)
Here, each diagonal element $m_i$ is the product of elements $t_i$ and $w_i$ from weighting matrices $T$ and $W$, respectively. Following the formulation used to weight the GHI in Secs. 3.1 and 3.2, we create the multiobjective global isotropy index ($MWGII$), as shown in Eq. (14)

$$\text{MWGII} = \max \min \frac{\sqrt{\sigma_{\text{min}}(\theta)M(\theta, \xi, \tau, \tau_{\max}) J(\theta)^T}}{\sigma_{\text{max}}(\theta)M(\theta, \xi, \tau, \tau_{\max}) J(\theta)^T}$$

The $MWGII$ allows the quantification of kinematic dexterity, and by extension, morphological design quality with respect to both collision-avoidance capacity and mechanical advantage. The $MWGII$ serves as the basis of the proposed design function.

3.3 Proposed Design Metric. The design fitness metric proposed in this study, called $Q_{\text{MII}}$, is the product of the $MWGII$, which serves as the primary measure of kinematic and dynamic performance, and the penalty function $\Gamma$, which is a sigmoidal function of design complexity values and manufacturing costs. $Q_{\text{MII}}$ is defined in Eq. (15)

$$Q_{\text{MII}} = \Gamma(\Sigma \text{ complexity}) \cdot \Gamma(\Sigma \text{ cost})$$

The function $\Gamma$, defined in Eq. (16), represents the feasibility and desirability of an MII device design with respect to aggregates of design complexity and cost. These aggregates, explained in Sec. 4, are determined by the selection of linkage components and actuators, and by the distribution of those parts

$$\Gamma(x) = (1 + e^{(x-k)/\alpha})^{-1}, \ \alpha = 5$$

The sensitivity of the penalty function $\Gamma$ is adjusted using the value base, which can be set to reflect the designer’s perception of reasonable complexity or cost. As the value of input $x$, the assigned cost or complexity of a device design, moves above the upper limit established by base, $\Gamma$ goes to zero, indicating exorbitant cost (Fig. 7). For lower values of $x$, $\Gamma$ approaches 1 indicating acceptable cost and making $Q_{\text{MII}}$ solely a function of the $MWGII$. The behavior of the penalty function $\Gamma$ allows design cost and complexity to influence $Q_{\text{MII}}$ independent of the $MWGII$ values, thus promoting a fitness value that favors a balance between device functionality and economy.

4 Experiments

4.1 Design Space. The objective of these experiments is to optimize a robotic MII device design by maximizing the design fitness metric $Q_{\text{MII}}$ for given cost and complexity limitations. Optimization is conducted over four distinct parameter types: the number of DOFs, the rigid-body link types, the dimensions of the rigid-body links, and the actuator types used for each DOF. Each parameter type has a clearly defined design space from which several design perturbations can be composed, and these spaces are searched by the methods deemed for their size and type.

The number of DOFs in the MII device is an integer parameter with a range of 5–30. In these experiments, the number of DOFs is equal to the number of joints in the MII device linkage given that only revolute joints are used; no compound joints such as spherical or helical joints, which contain more than one DOF, are considered. The number of DOFs does not include the prismatic motion of the MII device linkage base (Fig. 8), which moves to position the device as it penetrates the subxiphoid trochar. The number of DOFs for the MII device design is searched iteratively in these experiments.

The rigid-body links used in the MII device linkage are chosen from a set of four types: a lateral link whose length is perpendicular to the joints at its two ends (Fig. 9(a)), a right angle link whose length is perpendicular to one of its two joints and parallel to the other (Fig. 9(b)), a bent tube link whose joints are tangent to its curvature (Fig. 9(c)), and an angled link whose length is parallel to one joint’s axis and askew from the other by an angle $\theta$ (Fig. 9(d)). The type and distributions of links in an nDOF MII device design are chosen by a genetic algorithm (GA), explained in Sec. 4.2.

The dimensions of the chosen link types have bounded, continuous ranges, and each link type has a specific number of dimension variables. These variables and their ranges are listed in Table 1. Link dimensions are searched by a nonlinear gradient-based search algorithm, explained in Sec. 4.2.

The actuators used at each joint are chosen from a pair of types: a commonly available but low-torque micro electrical motor (Fig. 10(a)), and an expensive and sophisticated, but more powerful cable-driven pulley mechanism. These actuators were chosen to represent the actuator design space in these experiments because they are often used in the design and implementation of small-scale manipulation systems like the one being designed here. The arbitrary cost and complexity values of these actuators, based upon the authors’ perceptions, are shown in (Fig. 10(b)). The actuator types, like the link types, are searched by GAs.
4.2 Optimization Process. The optimization process used in these experiments consists of a nested set of three parameter optimization loops, shown in Fig. 11. The outermost loop is an iterative sweep of the range of DOFs available for the design of the MII device. As mentioned, the number of DOFs ranges from 5DOF to 30DOF.

For each nDOF iteration, the middle loop performs a genetic algorithm optimization of that nDOF morphology by randomizing the selection of rigid-body links and actuators that comprise it. The genetic algorithm is facilitated by the MATLAB® GENETIC ALGORITHM AND DIRECT SEARCH TOOLBOX. The GA begins with the creation of a 16 member initial population by mutation of the given initial MII design morphology. As each member of the population is simulated performing the intended subxiphoid cardiothoracic intervention maneuver, the device’s link dimensions are optimized within the inner loop, the nonlinear gradient-based search, to produce the morphology with the highest $Q_{MII}$. The nonlinear search of rigid-body link dimensions is supported by the MATLAB® OPTIMIZATION TOOLBOX, and is performed until the changes in $Q_{MII}$ fall below the specified gradient tolerance of 0.005, or until the number of search iterations reaches the maximum of 250.

After all members in a GA generation have been optimized with respect to $Q_{MII}$, those members with the highest $Q_{MII}$ values are chosen as the basis of the future crossover generation. This process repeats until the evolution of the MII device design $Q_{MII}$ approaches a plateau, at which changes in $Q_{MII}$ fall below the set threshold of 0.005, or until the maximum number of generations, 50, have been created.

At the conclusion of the optimization process, there is one maximum $Q_{MII}$ value for each number of DOF in the outer loop. The MII device design associated with the largest of these values is deemed the best design for the device.

4.3 Design Constraints. The optimization process is limited not only by the range of the parameters in the design space, but also by a logistical, manufacturing-based constraint. Because of the complexity and bulk of the cable-driven mechanisms and the specialized joints that they require, the MII device may not include any electrical motor actuators distal to a cable-driven actua-
tor. This, the authors assume, would lead to problems with routing both electrical connections and actuation wires through any one joint.

4.4 Simulation Settings. Simulations of the MII device executing the intended task are performed using the authors’ MATLAB® based kinematically redundant robotic manipulator (KRRM) simulator, and are based on the authors’ weighted isotropy metrics, presented in Sec. 3.2. The variable $\beta$ used in the calculation of the collision-avoidance function $w_i$ is set to 0.25, while the variables $\lambda$ and $\eta$ used in the calculation of the torque penalty function $t_i$ are set to 0.95 and 0.5, respectively.

The dynamics of the MII device simulation are based upon accelerations due to gravity and rigid-body motion and upon the mass of the actuators used in the design. The total mass of the links used in the designs is assumed constant. The MII device, during the simulation of the interventional maneuver, is not required to apply any external forces at the tool tip; thus, all required torques arise from gravitational and inertial forces. During task simulation, joint torque is minimized locally using inertia-matrix based control methods [30,31].

4.5 Initial MII Device Design. The initial MII device was designed specifically to perform the intended subxiphoid cardio-thoracic maneuver while avoiding collisions with the heart or surrounding organs that could cause collateral damage. This 20DOF device, shown in Fig. 12, was designed by the authors’ physical intuitions, without the use of optimization algorithms or weighed isotropy measures, and does not take into account design cost and complexity. The number, size, and distribution of linkage parts were determined in part by the authors’ previous manipulator design experience, but were determined primarily by the geometry of the intended workspace. The $MWGI$ of the initial device design is relatively high at 0.0328, as it was flexible enough to avoid collisions while maintaining high dexterity (Fig. 13). The $Q_{MWGI}$ value, however, is a paltry $2.0 \times 10^{-14}$ with respect to the authors’ cost and complexity limits of 120 units. This indicates that the 20DOF design is exorbitantly expensive and complex for its performance level.

The results of the following optimization experiments show that designing a MII device by the comprehensive design fitness measure like the $Q_{MWGI}$ can yield devices that achieve performance levels close to that of the 20DOF MII device, but without the high degree of cost and complexity.

5 Results

5.1 First MII Device Design Optimization. With the same cost and complexity limits of 120 units used to assess the design fitness of the 20DOF MII device, the proposed optimization algorithm was used to create a less costly but equally effective device. After 37 GA generations, the optimization algorithm produced a 13DOF MII device design having a $MWGI$ value of 0.0297, approximately 91% of the 20DOF device performance value, but having a $Q_{MWGI}$ value of 0.0185, which is 12 orders of magnitude greater (Fig. 14). This indicates that the design cost and complexity conform fairly well to the limitations of 120 units placed on them. The 13DOF device contains only cable-driven actuators despite the fact that they are more complex and costly than stepper motors. This is likely due to the fact that stepper motors, regardless of their economy, cannot supply the torque necessary to power the device’s motion in outstretched configurations. The 13DOF device negotiates the heart with no incidence of collision and with high kinematic isotropy, as shown in Fig. 15, meaning that motion was relatively smooth.

5.2 Second MII Device Design Optimization. A second optimization experiment was run using more conservative complexity and cost baselines to observe the effect that these settings have on the performance of the MII device. In the new settings, the complexity limit is set to 100 units and the cost limit is set to 100 units. As was expected, the dramatic decrease in design complexity and cost limits caused a dramatic change in the morphology and a slight drop in performance. The resulting 11DOF morphology has two fewer degrees of freedom than the previously optimized device, yet still has relatively high $MWGI$ value of 0.0277.
The \( Q_{\text{MII}} \) value remains acceptable at 0.0140, but has decreased by 22% from the 13DOF device. Still, this device executed the intended task without incidence of collision with the heart or surrounding organs, as seen in Fig. 17.

5.3 Third MII Device Design Optimization. The previous design optimization attempts yielded progressively “cheaper” designs as cost and complexity limitations were decreased. However, this frugality comes at the expense of device performance. This trend indicates that there is a threshold beyond, which further cost penalties will degrade performance so much as to render the device clinically useless, and this fact is evidenced by the results of the third optimization experiment. In this experiment, the cost and complexity limits of the MII device are set to 80 units. The resulting 7DOF manipulator, shown in Fig. 18, has a comparatively low \( MWGII \) value of 0.0102, and a low \( Q_{\text{MII}} \) value of 0.007. Given that torque requirements have not changed significantly, the low \( MWGII \) value means that collision-avoidance capability is greatly reduced and that undesired anatomical contact is far more likely. In fact, there were four configurations of the 7DOF during simulation at which significant contact with anatomical structures was made (Fig. 19). In this case, the clinical inefficacy of the device outweighs its high economy and makes it an unsuitable MII device design.

5.4 Optimization Trends. From these three MII device design optimization experiments, it is apparent that there is a tradeoff between design complexity and device performance, and that the limitations placed on the design complexity must be chosen carefully to produce an economical design that still yields acceptable clinical value. The relationship between complexity and design is elucidated by the optimization data from the second experiment, where the optimal design is found at 13DOF. Figure 20 illustrates the points at which the \( MWGII \)-based performance...
level begins to plateau and the $Q_{\text{MM}}$ begins to decline. It is at some point before the $W_{\text{GGI}}$ plateau and after the $Q_{\text{MM}}$ decline that the optimal design is found. This same trend is also evident in the results of the first and third experiments.

6 Conclusion

The results above show that weighted isotropy metrics, when combined with an intelligent set of design penalty parameters, can significantly reduce the cost and complexity of a kinematically redundant MII device design while ensuring acceptable clinical value. Though the proposed $W_{\text{GGI}}$-based fitness metric $Q_{\text{MM}}$ is heuristic in nature, it clearly elucidates the relationship between design complexity and clinical function and effectively facilitated the redesign of a relatively exotic $2\text{DOF}$ MII device into a less complex but equally effective $1\text{DOF}$ alternative. Increasing the economic feasibility of this MII device while maintaining its clinical function makes it a much more attractive candidate for development and production.

These results also show that by increasing the capacity of complexity and cost penalty parameters, we can force the development of cheaper designs at the expense of clinical performance. The use of exorbitantly greedy penalty parameters in the third optimization experiment resulted in a design that is very cheap, within the context of the penalty function definition, but which performs so poorly as to defeat the clinical purpose for its design. This metric can therefore be used not only to capture the cost/function tradeoff relationship, but also to establish the feasible limits of that tradeoff.

Future research endeavors will be focused on developing a more comprehensive, task-sensitive design objective function. The objective function employed in this study was a meaningful but abstract formulation that considered only the totality of effects that certain design and performance parameters have on the quality of a device design. Further study will be conducted to systematically determine which design parameters have the greatest bearing on the relationship between manipulator performance and design costs.

Additional work can be done to improve the resolution and accuracy of the 3D models used for simulation, and to improve the robustness of the optimization process by expanding the design space to include more actuator and link types. The authors acknowledge the fact that the simulation models and the MII device design space were rudimentary compared with what would be considered for an actual, functional prototype design. This study, however, has proven the efficacy of balancing design cost and $W_{\text{GGI}}$-based performance metrics as a means of designing useful but economically feasible MII tools. The concepts developed here have availed the possibility of more thorough and cogent design optimization experiments in the future.

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