Chapter 7

Conclusion

The main topic of this study was the optimal dimensional synthesis of planar parallel manipulators by means of numerical optimization techniques. In order to accomplish this, three specific issues needed to be addressed. These three issues, and achievements in each of these areas are discussed separately in the next three sections. In the final section of this chapter, recommendations for future refinement and development of the methods, developed during this study, are proposed.

7.1   Optimization algorithms

Two optimization algorithms were proposed and evaluated in the first part of this study. The spherical quadratic steepest descent (SQSD) optimization algorithm, presented in Chapter 2, provides a method for solving unconstrained optimization problems. Comparison of the performance of the algorithm with the classical steepest descent (SD) method indicates that the introduction of spherical quadratic subproblems dramatically improves the robustness of the method. In addition, the elimination of explicit line searches results in a much more efficient method than the SD method. The SQSD method per-

forms well when compared to conjugate gradient methods. Particularly impressive is the ability of the SQSD method to solve ill-conditioned problems containing large numbers of variables, where the conjugate gradient methods break down, or take very long to converge. A proof of convergence for the SQSD method applied to general positive-definite quadratic functions is also given.

A version of the SQSD method, modified to solve constrained problems, is presented and tested in Chapter 3. This method is called the Dynamic-Q method, since the dynamic trajectory method of Snyman (see Appendix B) is used to solve the successive quadratic subproblems via a penalty function formulation. When compared to an SQP method using standard test problems, the Dynamic-Q method exhibits comparable efficiency and robustness. The Dynamic-Q method is however believed to be superior when applied to practical engineering problems containing phenomena such as numerical noise (as illustrated in Chapters 4 to 6). It also has the advantage that no Hessian information is required. This makes it a much more viable method for problems with very large number of variables.

User-friendly implementations of the SQSD and Dynamic-Q optimization algorithms have been programmed in FORTRAN and MATLAB.

7.2 Workspace determination

The original chord method, described in Appendix C, has been refined during the course of this study. The refinement, whereby the number of variables, contained in the optimization problem used for determining successive points on the workspace boundary, is reduced, results in a more efficient and accurate algorithm than the original implementation (see Section 5.4). In addition, a new scheme for determining bifurcation points has been developed in Section 6.4. This new scheme is slightly less accurate than the original

methodology, but more generally applicable.

For the first time, the chord method has been applied to the determination of constant orientation workspaces of planar 3-$R\underline{P}R$ parallel manipulators. Additionally, the numerical multi-level optimization approach for dextrous workspace determination, based on the chord method and presented in Section 5.5, has successfully been used to determine dextrous workspaces of planar parallel manipulators. Constant orientation and dextrous workspaces are determined accurately and automatically.

The determination of workspaces of tendon-driven parallel manipulators is a challenging problem because the workspace is dependent primarily on the forces in the tendons. When considering over-constrained manipulators this factor is particularly important, since there is no unique solution to the cable tensions for a given position and load on the platform. Two new methodologies for determining cable tensions are proposed in Section 6.3.3. A further problem, related to workspace determination, is that the cable tensions may be discontinuous as the platform moves from one configuration to another. Two methodologies for determining workspaces of planar tendon-driven manipulators were developed. The first method, based on the discretization approach, is robust but in practical terms the accuracy of the method is limited by its high computational cost. As an alternative, the chord method is successfully applied to determining workspaces of tendon-driven manipulators, resulting in accurate and efficient determination of workspace boundaries. These methodologies and results are presented in Chapter 6.

7.3 Dimensional synthesis of manipulators

In Chapter 4 various strategies for optimizing parallel manipulators are investigated. The methodology thought to be the most practical is that presented in Section 4.7, which seeks to optimize the performance of the manipulator,

while ensuring that a certain prescribed workspace can be reached. This methodology is successfully applied to a 2-$R\underline{P}R$ planar parallel manipulator, and then to the more complex 3-$R\underline{P}R$ manipulator in Chapter 5. For the 3-$R\underline{P}R$ manipulator various approaches are suggested for dealing with the orientational degree of freedom of the manipulator. In all cases optimal designs were found efficiently using the Dynamic-Q algorithm developed in Chapter 3.

An alternative synthesis approach was adopted in Chapter 6 for tendon-driven parallel manipulators. Here the objective of the optimization is to maximize the dextrous workspace which can be reached by the moving platform. The discretization method is used to evaluate the workspace areas in this case. The Dynamic-Q method proves its robustness by optimizing the manipulator, despite the numerical noise caused by determining the workspace in this manner.

7.4   Recommendations

It is believed that the full potential of the numerical methodologies developed in this work, applied here to planar manipulators, will be demonstrated when applied to more complex spatial cases. In terms of workspace determination it appears that the method for determining dextrous workspaces, presented in Section 5.5, can be extended to spatial parallel manipulators as well. The resulting methodology may provide an efficient numerical solution to this challenging problem.

Similarly, the constrained ℓ_1-norm approach developed in Section 6.3.3 for determination of cable tensions of overconstrained tendon-driven manipulators, as well as the methods for determining workspaces of tendon driven manipulators, could all be extended to the spatial case.

Finally, the methodologies for manipulator dimensional synthesis provide a meaningful alternative to existing methods. The formulations should be easily extended to include other performance criteria, and more complex manipulators. The inclusion of more design variables in these cases should easily and efficiently be dealt with by the Dynamic-Q method.