Chapter 5

5 CONCLUSION

The main objective of this study has been achieved. From the results presented in this study, it is evident that the proposed optimization approach is indeed a *general* numerical method by means of which different types of workspaces of different classes of mechanical manipulators may *easily* be determined. The generality of the method is illustrated by the fact that the optimization method was successfully implemented for a redundantly controlled planar serial manipulator, a planar Stewart platform as well as a spatial 6–3 Stewart platform.

The validity of the optimization approach is established beyond doubt by a comparison of the results obtained for the planar manipulators with those reported by Haug et al. [8, 12] in their state-of-the-art articles on the continuation method. This is particularly reassuring and encouraging since Haug is considered one of the world's leading authorities on computer aided design of mechanical systems [45, 46]. Not only was the outer accessible workspace boundaries mapped, but also the curves connecting the bifurcation points situated on the outer boundary with those situated inside the accessible output set.

The mapping of the curves connecting the bifurcation points of the planar Stewart platform show that the optimization method easily handles the situation where the upper platform becomes collinear with one of the actuator legs, resulting in a singularity. Once all the singularities are identified, any required path can be planned to avoid those regions where the control of the Stewart platform becomes a problem. The method is therefore successful in assisting in the characterization of the workspace and of great potential importance with regard to the control of manipulators.

The description of the behavior of the planar manipulators led to a new notation for labeling the bifurcation points and curves of the workspaces. This notation arises in a natural way from the optimization approach, is generally applicable and easy to understand. Using this notation, the complete workspace may be described in terms of the behavior of the manipulator. This notation is more than a simple labeling since it allows for a concise and unambiguous description of the configuration of a manipulator at any allowable position and orientation. It is hoped that this notation will be accepted and adopted by workers in this field since, the belief is, that it will certainly assist in a clearer description of manipulator operations and thus will be invaluable with regard to communication between workers.

Of great practical importance is the treatment of dexterity requirements imposed on a Stewart platform. The optimization approach successfully determines different specified dextrous workspaces of the *planar* Stewart platform. Using the new notation, the boundaries containing the dextrous workspace are easily identified and labeled. Consequently the behavior of the planar Stewart platform when situated on these boundaries, may be described in detail.

As far as the *spatial* 6–3 Stewart platform is concerned, the workspace results obtained by the optimization approach gives a much more detailed description of the workspace than that previously reported by Liu et al. [18]. Here, for the orientationally unrestricted workspace, a single vertical plane of the accessible workspace was mapped and labeled using the optimization approach. The results show that mechanically infeasible regions are enclosed in the orientationally unrestricted workspace. Without the labeling notation suggested by the optimization approach, it may have been impossible for this important conclusion to be reached.

A very important achievement of this study is that an example of a dextrous workspace of the 6–3 Stewart platform was successfully mapped. The dexterity requirement is simple but of practical importance. It specifies a rotatability range for only one of the three orientation angles, with the other two orientation angles remaining fixed. The determination of this dextrous workspace is very significant because, as far as the author is aware, such a mapping has not previously been performed for the spatial case. In general of course, a dextrous workspace will imply that dexterity requirements are specified for all three orientation angles. There is no reason to believe that the current method will not be able to achieve this as well.

The proposed labeling notation was easily extended to label the surfaces containing the dextrous workspace as well. As with the planar Stewart platform, it was shown that the optimization method is a powerful tool with which the practical useful dextrous workspaces can be determined and characterized.

It is hoped that this study will lie the foundation for the development of a general and rational synthesis design tool for parallel manipulators. However, reviewing the research reported here, certain further and immediate research tasks are identified. Although the planar Stewart platform was analyzed in detail as far as the reachable and various dextrous workspaces are concerned, this is not so for the spatial platforms. An extension of the research done on the 6–3 Stewart platform workspaces remains to be done where the *full* orientationally unconstrained accessible workspace and any *general* specified dextrous workspace is to be mapped and labeled. In addition, the work must be extended to the *general* 6–6 Stewart platform.

Another outstanding problem of important practical value, is the determination of the *mechanically* feasible orientationally unconstrained reachable workspaces for both planar and spatial Stewart platforms. Here, actuator leg interference and actuator joint orientation range limits need to be considered as additional constraints in the implementation of the optimization method.

This study has important potential impact for the manufacturing industry of South Africa and other developing countries. The implementation of this technology lies primarily in retrofitting existing non-CNC milling equipment to increase their capability at a lower cost than that of the alternative of purchasing traditional 5-axis machining centers [47]. One of the industries that can benefit from such a development is, for example, the plastic injection molding industry, where mould manufacturing is an expensive and time consuming operation.

As a first step towards the successful implementation of such a retrofit, it is foreseen that a planar type Stewart platform be fitted to an existing 3-axis machining center that will result in 4-axis milling capabilities. A planar type manipulator will be easier and cheaper to manufacture than a spatial manipulator, and such a 4-axis CNC mill will, to some extent, fulfill in the machining requirements of the plastic injection molding industry. It is however envisaged to extend the machining capability to a higher competitive level by the eventual fitting of fully spatial Stewart platforms. This will only be possible through the use of sophisticated and powerful design tools of which, it is hoped, the foundation was laid here.

Further future research to be done also includes the extension of the optimization approach to incorporate the mapping of the so-called *quality index* [13] of any configuration within the mechanically feasible dextrous workspace. This will give further characterization of the workspace and provide valuable information regarding the utility of various regions of the workspace. The quality index should also reflect any singularities, and therefore give an indication of the safe regions within which the manipulator can be maneuvered and controlled.

In conjunction with the mapping of the quality index, adjustable positioning of the actuator leg joints on the base and moving platforms can be utilized to optimize the mechanically feasible dextrous workspace for any required machine tool path.

A further important point which emerges from this study and is worth mentioning relates to forward kinematics. The exercise of mapping bifurcation curves leads to the possibility of successfully performing forward kinematics through an optimization approach. This may lead to a competitive continuation method and therefore justifies further investigation.