CHAPTER VIII

CONCLUSION

8.1 Dissertation Summary

In this work, we consider the problem of computing all force closure grasps of an object that is represented by a set of discrete contact points. The problem is classified into four settings according to the presence of friction and the dimensions of the objects. For each setting, a novel algorithm is proposed. Additionally, in the case of frictional planar grasping, we propose a novel single query force closure assertion method. The proposed algorithm, to the best of our knowledge, shows very promising performance in both time and accuracy of the output.

In the case of planar objects, we propose output sensitive algorithms that compute all force closure grasps. Even though the number of solutions K is in $O(n^4)$ and $O(n^3)$, respectively for the frictionless case and the frictional case, the proposed algorithms are able to yield the solution within time complexity of $O(n^3 \lg^2 n + K)$ and $O(n^2 \lg^2 n + K)$, respectively.

For 3D objects, we propose a heuristic method based on a necessary condition of force closure. The method rejects most of non force closure grasps while accepts some elusive ones. All force closure grasps are accepted by the method. The method is designed to work as a filter by providing high rate of specificity while requiring only minuscule computational effort. With this methodology methods, a filtering approach is proposed; a grasp is first validated by our method. If a grasp is accepted by the method, another complete test of force closure is consulted again to verify the force closure property.

All proposed algorithms are implemented in C++ and are empirically compared with same existing algorithms in the literature. The evidence shows that our algorithms outperform the existing methods in term of speed. The algorithms are also tested in the accuracy aspect. Interestingly, the existing methods in the literature exhibit dramatically different numerical stability; some methods are very prone to malicious input while some are very robust. Our proposed methods show relatively high robustness. In most cases, their accuracy are on par with the most accurate existing methods.

The key idea of the proposed algorithms is the use of projective geometry in the computation. It is long known that the force closure property does not take into account the magnitude of wrenches. However, this fact is neither explicitly exploited nor correctly employed. In our work, we use projective geometry to correctly represent 3D wrenches. From this stand point, we derive conditions, based on several problem reductions, that allow efficient implementation to be realized. Additionally, we also take into account a priori knowledge of the problem at hand, i.e., the nature of forces and torques in the grasping problem, as a motivation in deriving a condition. This knowledge helps establish an efficient algorithms.

8.2 Further Improvement and Extension

In this section we list some future improvement and extension that could be done to this work.

1. **numerical stability analysis:** Of all the methods there is shown as vestige in the empirical comparison the nonconformity of the result. This is in most part the result of round-off errors in floating point operation. Though this work put much labor into the investigation on the cause of this disagreement, there still left open the theoretical analysis on numerical stability of the methods, both the existing methods and the proposed methods. The result of such analysis will undoubtedly provide improvement to this work.

2. **heuristic improvement:** Another vexation of the presented algorithm is that there is still no efficient test of frictional 3D grasps. Even though the empirical result shows that it is at the verge of completeness, however, the proposed method is not only being incomplete but also being contrived as such. Hence, obvious improvement is on the heuristic approach. The condition might be improved such that it can be computed more efficiently or that it yields less fault.

3. **better data structure implementation:** The output sensitive data structures used in the case of reporting all planar grasps are selected based on the merit of ease of implementation. There exist other data structures that give better complexity but requires much greater implementation effort. Incorporating such data structure could result in better performance.

4. **filtering framework in other grasp synthesis:** The proposed heuristic for 3D grasping presented in this work is used in computing all force closure grasps. However, due to its modular nature, it can be incorporated into other grasp synthesis schemes, especially in the case of discretized input. However, one could argue that the benefit of the heuristic shown in the work is based on a fact that, for all possible grasps on an object, there are relatively large number of non force closure grasps, thus the advantage of the heuristic is dramatically vivified. Extending our heuristic approach to other grasp synthesis schemes is

an interesting topic to be further investigated. One might consider using other appropriate necessary conditions in the heuristic.

8.3 Discussion

An autonomous robot that accomplishes a required task with minimum supervision is a goal yearned by most researchers. A similar goal is also set for the grasping problem. It is the uttermost goal of this dissertation to, at least, provide a stepping stone to that problem.

Perhaps, the most interesting aspect of this dissertation lies not in the introduction of the algorithms but rather the vivification of two aspects: 1) the use of discrete contact point model, and 2) the need to compute all force closure grasps. In this work, both aspects are reckoned to be essential to solve the ultimate problem in grasping. Discrete contact points suit more to the data acquisition sensors, such as a laser range scanner or a stereoscopic camera which are widely available. Discrete contact point model also calls forth the need to handle input of a large number of contacts. Though it is possible to approximate the scanned data with one polynomial, this approach suffers from the high cost of curve fitting and the accuracy problem from Runge phenomenal. Spline fitting, arguably, reduces the effect of both problems but the result is still a large number of polynomials. In fact, when the resolution of the scan is large enough, spline fitting results in similar representation of discrete contact points. We reckon that impromptu grasping has to directly consider this problem. Evidently, this problem is included as one objective of this dissertation.

Computation of all force closure grasps is, by far, no less important than the use of discrete contact points model. Besides the decoupling of hand implementation and task planning which are the direct benefit of this approach, all force closure grasps, or more generally, a large number of force closure grasps of an object are very important to impromptu grasping. Since every realization of a mechanic system always inherits some error, it is presumptuous in the extreme to suppose we could ever place a contact with perfect accuracy on the required position. This problem is long discussed by the early works in grasping and the direct counteraction is to use a grasping solution that such inaccuracy is not a problem. Independent contact regions are an obvious way to describe the accuracy invariant solution. With a large number of grasping solutions, it is possible to calculate larger independent contact region. However, computing independent contact regions from a set of discrete contact point solutions is a problem yet to further investigate. This also marks another extension to our works.

Inevitably comes with these two emphasized aspects is the problem of computational effort.

Using discrete contact points result in an enormous number of contact points of which all force closure grasp must be computed. The number of the solutions can be as high as $O(n^7)$ in the case of 3D frictionless grasp. It is precisely this problem that this entire dissertation tries to cope with. We show that, at least, there are some solutions to the problem; it is possible to compute the solution in much lesser time than any existing method and there are many possible improvement that could be done. Moreover, our proposed method is also inherently parallel. Thus the benefit of multi core CPU which is the current trend in CPU design can be effectively harvested.

Finally, the filtering framework which are utilized in the case of 3D grasp provides another promising approach to the problem. As discussed in Section 8.2, several existing methods can make use of this framework. A straightforward adoption of the framework may be the generate-and-test approach. The framework is shown that a speedup factor of 20 folds is achieved in many cases. Arguably, this approach is maybe the best in time constrained situation since we can guarantee running time. This is very crucial property for real world application.

The author strongly believe that, with the proposed algorithm and the proposed approach, we could see many interesting, or the ultimate, solution to the grasping problem in the near future.