Prof. Alessandro De Luca, Editor
Dipartimento di Informatica e Sistemistica
Università degli Studi di Roma "La Sapienza"
Via Eudossiana 18, 00184 Roma, ITALY

Dear Prof. De Luca:

Please find enclosed three copies of a revised version of paper #F-99043/G-97159, "Measuring and Reducing the Euclidean-Space Effects of Robotic Joint Failures" by James English and myself, as you requested in your letter dated July 19, 1999. (I did not receive your letter until Aug. 9 due to an incorrect postal code, please note that the correct code is: 47907-1285)

From your letter it is clear that your main concern is with the realism of the failure assumptions used in our work. I believe that the assumptions are very realistic and have tried to address this in the manuscript by adding a paragraph to the introduction. The failure model and associated assumptions are based on the specifications given by the two agencies that funded this work: NASA (who wanted to guarantee that manipulator failures would not damage a spacecraft) and Sandia National Laboratory (who wanted to guarantee that manipulators used for cleaning up nuclear waste would not fail and cause collisions that would release radiation). For both of these agencies, two of their main concerns were:

1. How can I prepare for a possible joint failure so that if a joint on my robot fails and moves in an uncommanded manner, I can minimize the likelihood of collisions with my environment?

2. If one of my joint's motion is unreliable (either due to joint failure or sensor errors), how should I control the remaining joints in order to minimize the effect of the unreliable joint on the task that I am performing?

An additional constraint, due to safety considerations, is that the manipulator may *not* be moved at a high speed. This prevents failure recovery schemes that require large joint velocities to compensate for the motion of a failed joint.

From this realistic and very practical problem description, one can see that the issues involved are primarily geometric ones. For example, in case (1) it is important to be able to compute the swept volume resulting from a possible joint failure. Minimizing this swept volume by properly configuring the manipulator prior to the failure reduces the likelihood of a collision. This example is similar to what you call case (a) in your letter. Although we have analyzed the dynamics of free-swinging failures (we can provide our work: "An Example of Failure Tolerance through Active Braking," Second Int. Conf. Recent Advances in Mechatronics (ICRAM), pp. 181-186, Istanbul, Turkey, May 24-26, 1999.) the problem of calculating the workspace swept by the arm is a geometric one which only requires the dynamic parameters of mass and moment of inertia (this assumes that the motion of the failed joint is not underdamped, which is typically the case).

Regarding case (b) in your letter, if we know that a free-swinging failure has occurred in a joint, we can compute its joint value by using the equations presented in the paper without relying on the encoder. (Our ICRAM paper considers the dynamics of this joint's motion as the other joints are controlled to compensate for its failure.) However, if we assume that we are relying on an encoder that has failed, then we would use the analysis in the paper to configure the arm such that the error at the end effector due to the measurement errors in the failed encoder is minimized.

I hope I have expressed myself clearly and justified the assumptions that are made in the paper. I would greatly appreciate it if you would contact the Associate Editor and reconsider publishing the paper as a regular article. I would be happy to answer any questions or provide additional material if you like. However, if you feel that it must be a short paper, then I will agree to pay the overlength page charges.

Thank you very much for your time.

Sincerely yours,

Anthony A. Maciejewski
Professor of Electrical & Computer Engineering
Tel. (765) 494-9855
Fax. (765) 494-6951
Email: maciejew@ecn.purdue.edu

cc: Prof. Peter B. Luh, Editor-in-Chief
Enclosures

Response to Reviewer 1

Reviewer one had the following comments/suggestions:

1. **Why is derivative information needed and how do you deal with local minima?** The last paragraph of the introduction points out that all the common techniques of local redundancy resolution (gradient projection, extended Jacobian, and augmented Jacobian) require knowledge of the gradient. In the examples, we have added statements indicating we chose to use the gradient-projection technique in our simulations. (Although we would like to point out that it is not the purpose of our article to compare the relative merits of different redundancy resolution techniques.) With regard to local minima, this is a problem for any local optimization scheme. Several examples showing the details of how we deal with multiple local minima, disappearing local minima, and algorithmic singularities are given in [23]. We have also added an example to this paper (in the new section V) that includes a figure (new Fig. 5) which illustrates that multiple local minima do exist.

2. **How is the method used when it is not known which joint will fail?** Although the original manuscript focused on single joint failures, it is easy to combine these to form a comprehensive measure. We added a new example (in the new Section V) that uses a cost function that incorporates the possibility of any joint failure by summing all the jointwise measures. This example shows that there is a significant benefit to optimizing the measure. For a typical point in the workspace the difference between the best-case and worst-case cost function value is more than a factor of five. We have shown the cost-function value for all configurations reaching the example's workspace point.

3. **Define D-H parameter convention.** We now define the article's D-H convention when it is first introduced in Section II, as you suggested.

4. **What is the computational cost?** The proposed methods are not computationally expensive. For the seven-link RRC K-1207i, the gradient of even the most general method, including free-swining failures, multiple objects in multiple frames, and the possibility of any joint failure requires less than 4 ms to calculate on a Sun Sparc 10 workstation. We added a paragraph describing the computational cost at the end of Section VI.

Response to Reviewer 3

Reviewer three enumerated many detailed suggestions for improving the presentation of the paper. We have incorporated them all in the following manner:

1. Added the information from the Fig. 1 caption to text where it is referenced (end of first paragraph).
2. Reformatted the paper so the figures are close to their references in the text.
3. Added a reference to [VCW94].
4. Changed the text to note that the L-shaped object is only used as an example. (We wanted a simple object without symmetry along the primary axes.)
5. Added citations to [Lie77,KH83] for gradient-projection technique
6. Reworded paragraph after (37) as suggested.
7. Removed the words "not stable" as suggested. (We meant not constant, sorry for the poor choice of words.)
8. Made the two suggested wording changes.
9. Made the two suggested wording changes.
10. Changed order of sentences as suggested.
11. Changed wording to make it clear that not resolving redundancy is a good thing.
12. Since there are a large number of optimization criteria that have been proposed, rather than list them all we cite the review article [Nen89] that contains a catalog of 119 references (although not the most recent work).
13. Referenced conference version of this work in the footnote on the first page (IEEE style).

We have also corrected all seven of the minor changes pointed out by the reviewer.

Response to Reviewer 4

Reviewer four made the following comment:

> **Premise of pure joint sensor offset is not credible.** Our method addresses a much more general class of failures than only sensor-offset failures. For example, we considered free-swinging joint failures, i.e., where control torque is lost, in the second seven-link example of the original manuscript. In the new manuscript we have included an additional example of this type.
>
> With regard to sensor-offset failures, perhaps we were not clear in our description of what constitutes a calibration error. We used the word "offset" where "unknown value" was more appropriate. For use within the article's framework, a calibration error is any error that cannot be described as a function of configuration. Our interpretation of calibration error includes precisely the type of drift error you describe in your review. It also includes residual error after the arm has been calibrated, noise, and oscillation. These errors are not necessarily large. The examples use large errors for illustrative purposes.
>
> We have added wording to the calibration-error example (Section VI.A) to clarify this issue.