

This item was submitted to Loughborough's Institutional Repository by the author and is made available under the following Creative Commons Licence conditions.



creative commons  
COMMONS DEED

**Attribution-NonCommercial-NoDerivs 2.5**

**You are free:**

- to copy, distribute, display, and perform the work

**Under the following conditions:**

 **Attribution.** You must attribute the work in the manner specified by the author or licensor.

 **Noncommercial.** You may not use this work for commercial purposes.

 **No Derivative Works.** You may not alter, transform, or build upon this work.

- For any reuse or distribution, you must make clear to others the license terms of this work.
- Any of these conditions can be waived if you get permission from the copyright holder.

**Your fair use and other rights are in no way affected by the above.**

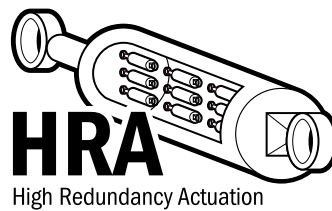
This is a human-readable summary of the [Legal Code \(the full license\)](#).

[Disclaimer](#) 

For the full text of this licence, please go to:  
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

# Technical Report CSG-HRA-2007-TR-4

## Requirements Analysis for High Redundancy Actuation



Date: 12th September 2007  
Revision: RCS *Revision* : 1.4  
Status: final report  
Distribution: open

THOMAS STEFFEN <thomas.steffen+hra@gmail.com>  
ROGER DIXON <r.dixon@lboro.ac.uk>  
ROGER M. GOODALL <r.m.goodall@lboro.ac.uk>  
ARGYRIOS ZOLOTAS <a.c.zolotas@lboro.ac.uk>

Control Systems Group  
Department of Electronic and Electrical Engineering  
Loughborough University  
Loughborough LE11 3TU, UK  
phone: +44 1509 22 7009  
fax: +44 1509 22 7008  
<http://www.lboro.ac.uk/departments/el/research/scg/>

**Keywords:** high redundancy actuation, linear actuation,  
requirement analysis, fault tolerance, robust control.

**Abstract:** This document introduces the idea of high redundancy actuation. Typical requirements for actuators in different applications are discussed, and a synthesis of the most important parameters is presented. To be successful, a high redundancy actuator needs to satisfy the same kind of requirements. Based on these, tentative parameters for an experimental verification of the high redundancy concept are proposed.

## Contents

<b>1</b>	<b>Introduction</b>	<b>4</b>
1.1	Actuator Configurations . . . . .	4
1.2	Motivation . . . . .	6
<b>2</b>	<b>Terminology</b>	<b>7</b>
2.1	General . . . . .	7
2.2	Actuators . . . . .	7
2.3	Faults . . . . .	7
2.4	Capabilities . . . . .	8
2.5	Control . . . . .	8
2.6	Fault Tolerance . . . . .	8
<b>3</b>	<b>Requirements of Example Applications</b>	<b>8</b>
3.1	Flight Control . . . . .	9
3.1.1	Physical Capabilities . . . . .	9
3.1.2	Control Capabilities . . . . .	9
3.1.3	Disturbance Handling Capabilities . . . . .	9
3.1.4	Example Capability . . . . .	9
3.2	Railway Active Suspension . . . . .	10
3.2.1	Physical Capabilities . . . . .	11
3.2.2	System Capabilities . . . . .	11
3.2.3	Example Capabilities . . . . .	11
3.3	Pick and Place Unit . . . . .	11
3.3.1	Physical Capabilities . . . . .	11
3.3.2	Control Capabilities . . . . .	12
3.3.3	Reliability . . . . .	12
3.3.4	Summary . . . . .	12
3.4	Jet Engine Guide Vane Actuator . . . . .	13
3.4.1	Physical Capabilities . . . . .	13
3.4.2	Control Capabilities . . . . .	13
3.4.3	Summary . . . . .	13

<b>4</b>	<b>Requirements Synthesis</b>	<b>14</b>
4.1	Overview . . . . .	14
4.2	Experimental Setup . . . . .	14
<b>5</b>	<b>Measuring Reliability</b>	<b>15</b>

## List of Figures

1	High Redundancy Actuator . . . . .	5
2	Parallel and serial configurations . . . . .	5
3	System capabilities in the BODE plot according to [Pratt2000]	10

## 1 Introduction

In fault tolerant control, it is necessary to safeguard a system against actuator faults. In mechanical systems, this is commonly achieved by using a small number of parallel actuators instead of a single actuator. Under typical dimensioning, any of these actuators is sufficient to keep the system operational. So even if one actuator fails, the remaining actuators are still able to achieve the desired function. A decrease in performance is acceptable and taken into account during the dimensioning of the system.

This project studies the use of a large number of actuator elements, which all work together as a single actuator assembly (or actuator for short). Any actuator element would not have enough power to satisfy the performance requirements. Depending on the exact configuration, travel and force of the actuator elements are added up, and together they exceed the requirements by a certain margin.

If one element fails, this will lead to a performance degradation, depending on the fault and the configuration. The dimensioning is such that the remaining actuators can still satisfy the performance requirements, so that the system remains operational. Because a high number of actuator elements is used in a redundant configuration, this approach is called a "High Redundancy Actuator" (see Figure 1).

### 1.1 Actuator Configurations

Due to the high number of actuator elements used, there are many possible configurations (or ways to arrange them, see Figure 2). The basic configurations to analyse are:

**Parallel elements:** this is the traditional configuration. The available force increases with the number of actuators, but the travel remains constant. So if one element locks up, the whole assembly fails.

**Serial elements:** the actuator is a chain of elements, so that the travel increases, and the force remains constant. If one element breaks loose, the whole actuator fails.

**Grid:** elements are in parallel and in series to increase both force and travel. Neither a blocked element nor a broken loose element leads to a failure of the assembly.

This project focuses on the grid configuration. It is the most flexible configuration, since it can be varied in a number of ways. The following aspects will be analysed in detail:

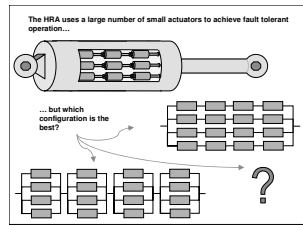


Figure 1: High Redundancy Actuator

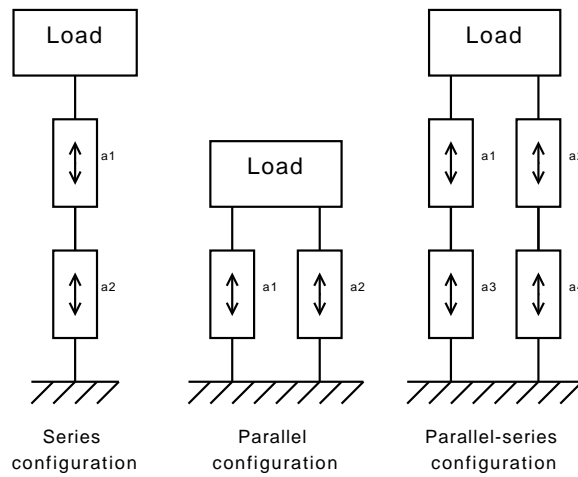


Figure 2: Parallel and serial configurations



- Determine the trade-off between more parallel or more serial actuators.
- Compare serial configuration of parallel actuators with a parallel configuration of serial actuators.
- Investigate the effect of different kinds of faults on the overall performance.

More complex settings are imaginable. They will be analysed if time permits and if it is scientifically relevant:

- several levels of parallel and serial actuators,
- actuators in a non-regular configuration,
- non-equal actuators, and
- additional resistant elements or force/travel limiting connections.

Finally the configuration can be extended from a basically 1-dimensional space to the full 3-dimensional space. The following steps may be of interest, but due to the complexity involved they may not receive a thorough treatment:

- Determine if a given configuration can leave the 1-dimensional space.
- Use actuators in 3-dimensional space to achieve 1-dimensional movement.
- Control the position of an object in 3 dimensions.

## 1.2 Motivation

The motivation of this project is to overcome limits and problems encountered with the traditional approach of parallel actuators. The High Redundancy Actuator is expected to demonstrate four main advantages:

- With serial actuation elements, the system remains operational even if one actuator is blocked.
- Using a high number of actuation elements will prove to be more efficient for single fault redundancy.
- Using a high number of actuation elements can provide graceful degradation.
- The configuration of actuation elements is flexible and can be tailored to meet specific requirements.

## 2 Terminology

Research into High Redundancy Actuation has only recently begun, which means that there is no little established terminology. An important result of this project will be to find appropriate terms to classify and denote the relevant concepts. Using a common terminology will make it a lot easier to communicate the results, and it will also help to give the deliverables a uniform appearance. The following terms are proposed so far, but future changes and extensions are to be expected.

### 2.1 General

The official project title is **intrinsically fault tolerant actuation through high redundancy**. While it is an accurate description of the project, it is too long to appear in the description of every publication. So the working subtitle should be **high redundancy actuation**. Every publication should contain these words in title or the keywords, preferably in both.

### 2.2 Actuators

The main idea of this project is to construct one **actuator** out of many **actuation elements**. It is essential to convey the semantic distinction between both. If it is necessary to stress the composite nature of the actuator, the terms **actuator assembly** can be used. The **actuator configuration** refers to the details of arranging the actuator elements.

### 2.3 Faults

Faults are an important aspect of this project, and it is useful to use common names for the most important faults. On the mechanical side, a **lock-up fault** denotes an actuation element that cannot move any more (it has become still). The opposite is a **loose fault**, where the element becomes free moving (e.g. broken into two parts). It is not clear whether any mechanical restraints remain in case of the loose fault (limits or linear bearing), and future definitions may be added to clarify this.

On the electrical side, there are two main faults. The shorting out of the electrical input is called a **short circuit fault**, while the loss of electrical connection (open circuit) is called **power loss fault**. Corresponding terms can be introduced for hydraulic or pneumatic systems if necessary.

When the whole actuator configuration or the system is considered, inoperability is called **failure**. This is to distinguish it from faults, which only

apply on a element. The goal of a fault tolerant system can be rephrased as “preventing a fault from becoming a failure”.

## 2.4 Capabilities

A physical performance measure of an actuator is called **capability**. These are relevant for the design of the system and the selection of the components, because certain **required capabilities** or **requirements** have to be satisfied.

The main physical values used to specify capabilities of a linear actuator are **force**, **acceleration**, **force** and **travel**. It is likely that further terms denoting additional requirements will be introduced for specific purposes.

## 2.5 Control

The control of an actuator is designed according to the specific requirements of the application. The most commonly used scalar values are **overshoot** (either absolute or relative to the step size) and **settling time** (with a given settling band). The frequency response is usually specified using exclusion areas in the BODE plot, but it is also possible to describe critical points such as the 3 dB **drop off point**, or the 1<sup>st</sup> and 2<sup>nd</sup> order **cut off frequency**.

## 2.6 Fault Tolerance

Different expressions are used to describe the fault tolerance of a system. The first distinction is the number of faults a system can cope with, accordingly it is called **single fault tolerant**, **double fault tolerant** etc. Another differentiation denotes the state of system after a fault occurred. **Fail safe** means that the system can return into a safe state (without any damage), while **fault operational** requires that normal operation can continue despite a fault.

# 3 Requirements of Example Applications

The High Redundancy Actuator is expected to be used as part of a larger system, so the requirements depend on the specific application of that system. In order to get an overview of typical requirements, the following four application areas are considered.

### 3.1 Flight Control

[Pratt2000] describes the typical requirements of a flight control actuator used to move a flight control surface. The main capabilities are highlighted here for comparison with other applications. For historical reasons, the actuator system always includes a position control loop, so the dynamic requirements are given for the closed loop.

#### 3.1.1 Physical Capabilities

The main physical capabilities of an actuator in flight control are force and speed. The force capability (called load) is defined for different operating regimes (nominal with both actuation elements and degraded with only one element active). There is also a maximum force specified, which is necessary to analyse the structural integrity of the actuator mounting.

The speed capability (called maximum rate) is specified at no load and at a moderate fraction of the minimum sustainable force (e.g. 60%).

#### 3.1.2 Control Capabilities

From a control perspective, the behaviour of the actuator is specified by the frequency response from set point to actual value. Usually, a region is defined in which the BODE plot has to be contained (see Figure 3). At low frequencies, a constant gain margin is allowed around the nominal gain. The lower gain boundary falls off towards higher frequencies, usually by 20 dB per decade first, and then by 40 dB per decade. The upper gain boundary is usually constant over all frequencies, or it may even fall off.

In addition, a lower phase margin may be specified. It is often proportional to the frequency. Both the lower phase and the lower gain margin can be specified separately for different stroke lengths.

#### 3.1.3 Disturbance Handling Capabilities

The response of the actuator to external forces (disturbances) is considered in the mechanical impedance. Both the minimum damping and the minimum stiffness are specified for a certain frequency range. Two sets of requirements are given for nominal and degraded operating mode.

#### 3.1.4 Example Capability

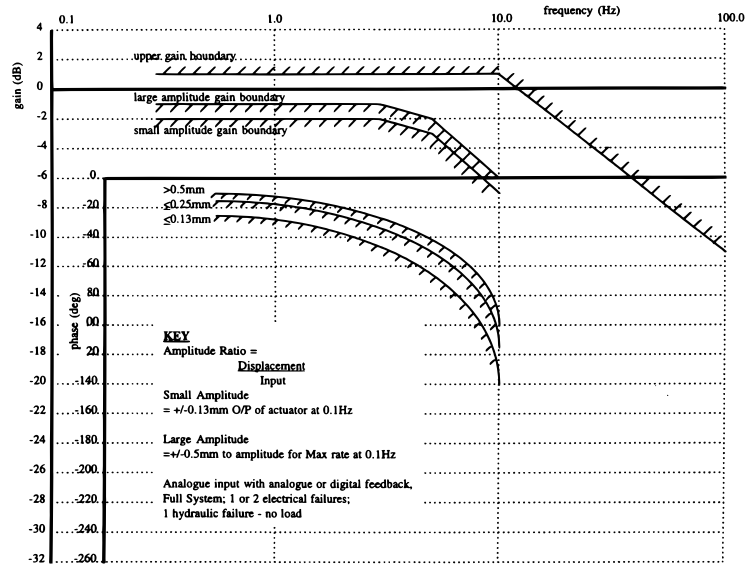


Figure 3: System capabilities in the BODE plot according to [Pratt2000]

Capability	Details	Value	Unit
force capability	“load”	>13 000	N
speed capability	“rate”	>0.1	m/s

System Capability	Details	Value	Unit
upper gain boundary		<1	db
lower gain boundary	(large amplitude)	>-1	db
lower gain boundary	(small amplitude)	>-2	db
1 <sup>st</sup> cut-off frequency	(lower limit)	>3	Hz
2 <sup>nd</sup> cut-off frequency	(lower limit)	>5	Hz
2 <sup>nd</sup> cut-off frequency	(upper limit)	<5	Hz

See Figure 3 for a graphical representation of the system capabilities.

### 3.2 Railway Active Suspension

Active suspension is a very different field of application for actuators. Unlike most actuators, which are designed to move a load, the active suspension is aiming to reduce the movement of the load. The goal is to transmit low frequencies from the track onto the load, but to isolate the effects at high frequencies. This has significant implications for the specification and design of the control system. The example used in [Goodall1993] will be used to illustrate this.

### 3.2.1 Physical Capabilities

The relevant physical capabilities are travel, speed, acceleration and force. They are specified as a peak required value, and as an RMS value (for thermal and energy supply design).

### 3.2.2 System Capabilities

The performance of the active suspension system is judged in terms of acceleration of the moving parts and the mean (RMS) displacement of the suspension. Of course this is subject to a certain load profile, but this is not specified in numbers, but by the train track taken.

### 3.2.3 Example Capabilities

Capability	Details	Value	Unit
travel capability	“displacement”	> 18	mm
travel capability	RMS	6	mm
speed capability	“velocity”	> 120	mm/s
speed capability	RMS	40	mm/s
acceleration capability	(have to check the source???)	> 2.25	m/s <sup>2</sup>
acceleration capability	RMS	0.75	m/s <sup>2</sup>
force capability		> 3.3	kN
force capability	RMS	1.1	kN

System Capability	Details	Value	Unit
body acceleration	RMS	2	% g (0.1m/s <sup>2</sup> )
bogie acceleration	RMS	10	% g (0.1m/s <sup>2</sup> )
suspension displacement	RMS	5	mm

## 3.3 Pick and Place Unit

SMAC is specialised in providing high speed pick and place solutions for the assembly of electronic components. The example given in [SMAC2007] gives a good overview of the main design goals for pick and place unit.

### 3.3.1 Physical Capabilities

Because the pick and place unit is considered as a system, the requirements are stated on a very high level, and they do not directly translate into physical

values. Basically the pick and place head has to move to specified sequence of points in space, without touching any of the exclusion areas. Some points have to be approached slowly or with a low force. The performance is then measured by the time it take to perform one sequence of movements. In the example, the movement includes distances of a total of about 250 mm, and two rotations of 180 degrees each. The given time to perform these moves is 300 ms.

From this sequence, it is possible to calculate the necessary acceleration. However, since the system cannot always use the full acceleration, and other functions need to be performed, this calculation only gives a rough estimate. It is however obvious that the force generated by the actuator and the weight of the pick and place head are the two main limiting factors. In the unit used, accelerations of up to 15 g (or 150 m/s<sup>2</sup>) are being used.

### 3.3.2 Control Capabilities

As it is typical for many robotic applications, the main concern from the control side is avoiding overshoot as much as possible, and limiting the speed or force at the endpoint of a move. Both overshoot and precision (settling band plus steady state deviation) are specified in absolute lengths.

### 3.3.3 Reliability

The reliability is specified by a load profile, and a desired maximum failure rate. In this application, operation is continuous (24h per day, 7 days a week). The desired time between servicing is in order of months to a year. As a secondary requirement, the heat build up in the device is supposed to be less than 20 degrees Kelvin over ambient temperature.

### 3.3.4 Summary

Capability	Details	Value	Unit
travel capability	“stroke”	> 30	mm
speed capability	“velocity”	> 1	m/s
acceleration capability		> 15	g (10m/s <sup>2</sup> )
cycle time		< 300	ms
actuator power cycle	within 2 s	40	%

System Capability	Details	Value	Unit
overshoot		< 10	$\mu\text{m}$
settling band	“accuracy”	< 10	$\mu\text{m}$
system use cycle	“continuous”	100	%
thermal steady state	“heat up”	< 20	K

### 3.4 Jet Engine Guide Vane Actuator

Some actuators are very closely integrated into a technical system, and a jet engine is an example for this [Dixon1999] . The inlet guide vanes are adjustable, and moved by an actuator. The forces involved are very impressive, while the other specifications are less demanding.

#### 3.4.1 Physical Capabilities

The force of the actuator is specified in two stages: the force the actuator needs to be able to drive, and the peak force it needs to be able to withstand. For clarification, these will be called active and passive force capabilities.

Because a linear gear is used, the travel of the actuator is not significant for the behaviour of the system. Instead, the required speed is specified by giving an amplitude that needs to be achieved at a given frequency.

#### 3.4.2 Control Capabilities

The control capabilities are not clearly specified for this application. The required response time is in the order of a fraction of a second, so it is not particularly fast. Obviously no significant overshoot is acceptable. The disturbance rejection of external forces is important.

#### 3.4.3 Summary

Capability	Details	Value	Unit
active force capability		> 22	kN
passive force capability		> 55	kN
frequency capability		> 2	Hz
amplitude capability		> 5	cm
speed capability	(resulting)	10	cm/s

System Capability	Details	Value	Unit
fault tolerance	to winding fault	1	faults
overshoot		< 10	%



## 4 Requirements Synthesis

### 4.1 Overview

Since the listed applications have the requirements given in different ways, it is very difficult to compare them. The following table assembles all the relevant capabilities that are used in more than one application. It can be concluded that these requirements are typical for actuators across different fields, and they are not specific to a certain application.

	control surface	active suspension	pick & place	inlet vane
Static Performance				
force capability (in motion)	13kN	3.3kN	-	55kN
acceleration	-	2.25m/s <sup>2</sup>	150m/s <sup>2</sup>	-
speed	0.1m/s	0.12m/s	1m/s	0.1m/s
travel	-	18mm	30mm	50mm
Tracking performance				
overshoot			0.01mm	10%
frequency	0-3 Hz	0.1-20 Hz	0-15 Hz	0-2 Hz

### 4.2 Experimental Setup

To study the behaviour of the High Redundancy Actuator in detail, two experiments are planned. The first is going to use electromechanical actuator elements (using an electromotor and a gear). The second experiment is using electromagnetic actuator elements, which use a moving coil in a magnetic field to produce the motion.

To make these experiments as realistic as possible, the requirements will be based on the key requirements identified in the four example applications above. Note that the planning of these experiments is not complete yet, so the figures given are only a rough estimate, and they are subject to change.

Capability	Experiment 1 Electromechanical	Experiment 2 Electromagnetic
Force	500N	100N
Acceleration	-	100m/s <sup>2</sup>
Speed	0.1m/s	1m/s
Travel	0.3m	0.2m
Load	10kg	1kg
Overshoot	1%	1%
Frequency	2Hz	10Hz

## 5 Measuring Reliability

One of the main objectives of this project is to develop an actuator with graceful degradation. However, measuring graceful degradation is conceptually very difficult. Further research is necessary to fully develop a suitable measure.

An example can demonstrate the conceptual problem. System A is assumed to be less likely to develop a fault, but a fault instantly renders it inoperable. System B on the other hand is more likely to experience a fault, but it can then continue with reduced performance. So it is only in system B that the operator has the option to take a corrective action after a fault is detected, such as preventive maintenance or a safe system shutdown. Either system may be considered superior, depending on the safety requirements of the specific application.

This demonstrates that reliability has several relevant dimensions. One way to describe this is by plotting a performance measure over the reliability probability. By definition, the performance will diminish with increasing probability, and for any real system it will reach zero as the probability approaches one. You can compare two systems by finding the reliability probability of the required performance. It is also possible to consider two different points: the performance for normal operation, and the performance necessary for a degraded mode (e.g. safe shutdown).

In order to study this in detail, a second set of requirements will be used to describe a degraded mode of operation. Some of the requirements (e.g. the part concerning the speed of the system) is reduced, while the required availability is set higher.

It is also possible to compare the reliability by using a risk analysis. In addition to the probability of different fault cases, the risk analysis also takes into account the (monetary) consequences. The result of the risk analysis is an expected cost (or return) for the operation of the system. Since this is a scalar value, it is easy to compare two systems. However, the full risk analysis can be difficult, and it requires a great number of variables to be determined.

Both approaches are valid and theoretical sound. Therefore, the plan is to try both initially. By comparing the results, it will be easier to select the way more suited for this project.

## References

- [Dixon1999] Dixon, R., Gifford, N., Sewell, C. and Spalton, M. C.: RE-ACTS: Reliable Electrical Actuation Systems, IEE Collo-

quium on Electrical Machines and Systems for the More Electric Aircraft, 1999.

- [Goodall1993] Goodall, Roger M.; Pearson, John T. and Pratt, Ian: Actuator Technologies for Secondary Active Suspensions on Railway Vehicles, in Proceedings of the International Conference on Speedup Technology for Raylway and Maglev Vehicles, No PS3-21, pp. 377-382, 1993.
- [Goodall2005] Goodall, Roger M.: EPSRC Project Proposal for Intrinsically Fault Tolerant Actuation Trough High Redundancy, Loughborough University, 2005.
- [Pratt2000] Pratt, Roger W.: Flight Control Systems-practical issues in design and implementation, Chapter 3 “Automatic flight control system design considerations” by S. Ravenscroft, TJ International, Padstow, Cornwall, 2000.
- [SMAC2007] SMAC Inc: Actuators by SMAC-New Ultra High Speed multi axis pick and place solutions, <http://www.smac-mca.com/smac-news-pages/ultra-high-speed-march2007.htm>, March 2007.