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Case Example of Systematic Design Engineering – Linear Friction Test Equipment

W. Ernst EDER[*1]

*1 Department of Mechanical Engineering
Royal Military College of Canada (retired)
107 Rideau Street, Kingston, Ontario, CANADA, K7K 7B2
eder-e@kos.net

Abstract

Engineering designers and students learning design engineering at times need good examples of procedure for novel design engineering. The systematic heuristic-strategic use of a theory to guide the design process – Engineering Design Science – and the methodical design process followed in this case study is only necessary in limited situations. The full procedure should be learned, such that the designer or student can select appropriate parts for other applications. The search for candidate solutions can be helped by this systematic and methodical approach. This case example is presented to show application of the recommended method, and the expected scope of the output, with emphasis on the stages of conceptualizing. The case follows a novel design problem of an item of laboratory equipment to support research into dry friction and wear of different material pairings.

Keywords: systematic design, abstract system models, search for alternatives, conceptualizing

1 Introduction

Practicing engineering designers and students learning design engineering at times need good examples of procedure for novel design engineering. The systematic and methodical design process followed in this case study is abridged from [1,2]. As shown in a paper presented at a previous conference [3], such a fully systematic procedure is only necessary in limited situations, when an engineering designer is faced with an unfamiliar and non-routine situation. Systematic design engineering, a procedure, is the heuristic-strategic use of a theory to guide the design process – Engineering Design Science [1,2,4,5] is recommended as guiding theory. Methodical design engineering is the heuristic use of newly developed and/or established methods within the engineering design process, including theory-based and 'industry best practice', strategic and tactical, formalized and intuitive methods. Systematic and methodical procedures have a substantial overlap, but are not co-incident. The full procedure should be learned, such that the designer can select parts for other applications.

A wide search for solutions, especially those that are innovative, can be supported by the recommended systematic and methodical approach. All generated alternatives should be kept on record, to allow re-tracing and recovery from subsequent detection of a better alternative. Each step in the procedure should be ended by selecting the most appropriate (one or two) solutions for processing, to control 'combinatorial complexity'.

The first case study, systematic according to the state of the theory and method at that time, appeared in 1976 [6] – a machine vice. The next appeared in 1980 [7] – a welding positioner. Six cases were published in 1981 and 1983 in German. A book published in 1982 [8] included these six cases (in English) plus two others – a riveting fixture, a milling jig, a powder-coating machine, a P-V-T-experiment, a hand winding machine for tapes, a tea brewing machine, a wave-powered bilge pump, and an oil drain valve – the powder coating machine, the tea brewing machine and the bilge pump only loosely followed the systematic method. Three further case studies were published in 2008 [1] – the tea machine revised to current systematic procedures with enhanced engineering information; re-design of a water valve [9] (first demonstration of re-design); and an electro-static smoke gas dust precipitator, with rapper for dust removal [10] (first demonstration of treatment of sub-problems). Three more were published in 2010 [2] – a trapeze demonstration rig [11], re-design of an automotive oil pump [12], and a hospital emergency bed, with sub-problem 'compensation for the support arrangement'. Other cases were presented at: DESIGN 2012 – leeboard mounting [13] and propeller shaft bearing arrangement [14], CEEA 2012 – bow thruster covers [15] and wind tunnel balance model support [16], CEEA 2013 – ship-to-shore gangway [17], TMCE 2014 – life-boat davit [18]. Several of these cases were designed by the author as sub-systems of the Caravan Stage Barge (http://www.caravanstage.org), which has been in operation in Canadian and U.S.A. coastal waters, and now in the Mediterranean, since 1995.

The primary purpose of these case studies is to present examples for procedural application of the recommended engineering design method that students and practitioners can follow and study to help learn the scope of the method and its models. This purpose has been applied in courses at the Eidgenössische Technische Hochschule (ETH) by Dr. Vladimir Hubka (1976-2000), at The Royal Military College of Canada (1981-2006) by the author, and at the University of West Bohemia (1990-present) by Professor Stanislav Hosnedl – who applied the systematic method for all levels of education and for industry consultations.

A secondary purpose was to verify and validate the theory and its models, and the method derived from the theory. The emphasis in all case studies was on the engineering design procedure and use of the models, the chosen technical systems were not necessarily optimal.

The systematic procedure must be adapted to the problem. An engineering designer can idiosyncratically interpret the models to suit the problem, using intuition, opportunism, etc. and thus develop information in consultation with a sponsor. Opinions will vary about whether a requirement should be stated in the class of properties as shown, or be appropriate in another class.

International standard ISO 9000:2005 defines two sorts of technological, artificial, human-made systems:

- *process systems*, consist of operations – transformation process (TrfP) transforming an operand;
- *tangible object systems*, consist of (tangible) constructional parts, with organs and functions – technical systems (TS), if they have substantial engineering content.

Figure 1 shows the basic model on which the theory and method are based.

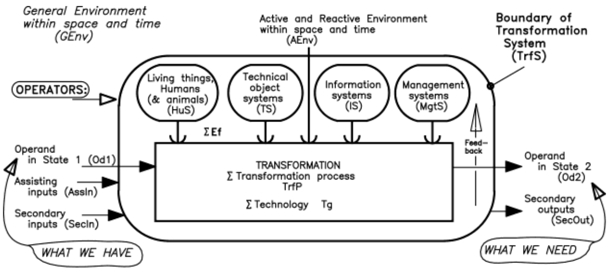


Fig. 1 General Model of a Transformation System [1,2]

This model of the transformation system declares:

An operand (materials, energy, information, and/or living things – M, E, I, L) in state Od1 is transformed into state Od2, using the active and reactive effects (in the form of materials, energy and/or information – M, E, I) exerted continuously, intermittently or instantaneously by the operators (human systems, technical systems, active and reactive environment, information systems, and management systems, as outputs from their internal processes), by applying a suitable technology Tg (which mediates the exchange of M, E, I between effects and operand), whereby assisting inputs are needed, and secondary inputs and outputs can occur for the operand and for the operators.

Using this model as basis, the full sequence of stages and steps of a novel design process are available in [1,2]. Using the same step designations, the case study procedure is summarized as follows:

* ***task defining***:

(P1) establish a design specification for the required system, a list of requirements;

(P2) establish a plan and timeline for designing;

* ***conceptualizing***

(P3a) from the desirable and required output (operand in state Od2), establish a suitable transformation process TrfP(s) to be accomplished by the TS(s) to be designed,

(P3.1.1) if needed, establish the appropriate input (operand in state Od1);

(P3.1.2) decide which of the operations in the TrfP(s) will be performed by technical systems, TS, alone or in mutual cooperation with other operators; and which TS(s) (or parts of them) need to be designed;

(P3.1.3) establish a technology (structure, with alternatives) for that transformation operation, and therefore the effects (as outputs) needed from the technical system;

(P3b) establish what the technical system needs to be able to do (its internal and cross-boundary functions, with alternatives);

(P4) establish what organs (function-carriers in principle and their structure, with alternatives) can perform these functions. The organs can be found mainly in prior art, especially the machine elements, in a new arrangement as proposed by Weber [19,20,21];

* ***embodying/laying out and detailing***:

(P5a) establish what constructional parts and their arrangement are needed, in sketch-outline, in rough layout, with alternatives;

(P5b) establish what constructional parts are needed, in dimensional-definitive layout, with alternatives;

(P6) establish what constructional parts are needed, in detail and assembly drawings, with alternatives.

The suffix '(s)' indicates that this TrfP(s) and/or TS(s) is the subject of interest, the system being designed. Only those parts of this engineering design process that are thought to be useful are employed. Such an 'idealized' procedure cannot be accomplished in a linear fashion – iterative and recursive working is essential, using analysis and synthesis [22]. This case example is presented to show application of the recommended method, and the expected scope of the output, with emphasis on conceptualizing. The embodying, laying out and detailing stages are regarded as more routine.

This report is a post-hoc reconstruction from the author's records. It is subjective, anecdotal, and cannot be verified. No attempt was made to create a formal research protocol. The process took place over a period of about four weeks, in the author's office at RMC, and even at home.

PROCEDURAL NOTE: Compare the output of each stage with the theoretical figures from [1,2] to check whether any important elements may be missing. Procedural notes such as this may be interspersed with the case to explain some aspects of the procedure.

2 Case Example – Linear Friction Test Equipment

In 1998, shortly after Dr Benabdallah joined RMC, (http://www.rmc.ca/aca/me-gm/per/benabdallah-h-eng.php) he wished to establish his research program, asking the author to help by designing a linear dry friction test apparatus.

Steps from the procedural model [1,2 (**figure 11.1**, p. 219-222)] were considered, and the following review cycle was applied for each step:

{Improve, optimize} – <Substantiate, evaluate,
select, decide> – {Verify, check, reflect}

**** task defining***:

(P1) establish a design specification for the required system, a list of requirements;

Requirements are listed only under the most relevant TrfP and/or TS-requirements class as judged by the engineering designer, and cross-referenced if they are repeated in any other relevant requirement class [2 (**figure 11.4**, p. 226-227)]. Indication of priority – F ... fixed requirement, must be fulfilled; S ... strong wish; W ... wish; N ... not considered

Rq1 OrgRq Organization requirements (Rq1A – Rq1E)
- F Design and manufacture by RMC, Dept of Mechanical Engineering.

Rq2 TrfRq Requirements of the Transformation (Rq2A – Rq2E)
- F No variation of contact force due to reversal of travel direction
- F Allow accurate setting of relative travel speed and length of travel
- F Minimum interaction between load force and friction force
- S Minimize backlash and clearance effects at all movable joints

Rq3 EfRq Effects requirements of the TS (Rq3A – Rq3C)
- S Smooth operation and easy adjustment

Rq4 MfgRq Manufacturing requirements
- F Fabrication in house, RMC Mech. Eng. Dept.

Rq5 DiRq Distribution requirements
- none

Rq6 LiqRq Liquidation requirements
- F Non-toxic materials – preferably aluminum

Rq7 HuFRq Human factors requirements (Rq7A – Rq7G)
- S Modifications will be made from tests of functionality

Rq8 TSFRq Requirements of factors of other TS (in their TrfP) (Rq8A – Rq8G)
- F Purchased components:
  - 1 Warner Electra 2000 ball-screw motor, in-line flange-mounted, 24” stroke, with brake
  - 1 Thompson Double System guideway with 4 pillow blocks, ½” dia shaft, 40” long
  - 2 Omega S-beam load cell, 100 lb capacity
  - 2 Omega Miniature OEM Button load cell, 250 lb capacity
  - 1 Spae Naur p. B256 ball-joint rod end, male ½” UNF-20
  - 2 Spae Naur p. B256 ball-joint rod end, male $^5/_{16}$” UNF-24
  - 2 Spirit level, trailer type
  - 6 Berg Te-F-Thane flanged bearing, p. 546, $^5/_{16}$” I.D., $^3/_8$” long

Rq9 EnvFRq Environment factors requirements, LC1 - LC7 (Rq9A – Rq9B)

Rq10 ISFRq Information system factors requirements, LC1 - LC7 (Rq10A – Rq10F)

Rq11 MgtFRq Management factors requirements
- *Rq11A Management planning, LC1*
- *Rq11B Management of design and manufacturing process, LC2 - LC4*
  - F Designing and manufacture super- vision by author and colleague.
- *Rq11C Design documentation, LC2*
  - F Original drawings to remain at RMC, copies held by author.
- *Rq11D Situation, LC2*
- *Rq11E Quality system.*
- *Rq11F Information requirements*
- *Rq11G Economic requirements*
- *Rq11H Time requirements*
- *Rq11J Tangible resources*
- *Rq11K Organization*
- *Rq11L Supply chain requirements*
  - F Obtain commercial items before start of detail design.
- *Rq11M Other management aspects*

DesRq Engineering design requirements for TrfP(s) and TS(s) (Rq12 – Rq14)
- None.

(P2) establish a plan and timeline for design engineering;

Detail design to be completed before end Aug. 1998.

**** conceptualizing***:

(P3a) **from the desirable and required output (operand in state Od2), establish a suitable transformation process TrfP(s)**;

(P3.1.1) **if needed, establish the appropriate input (operand in state Od1);**

(P3.1.2) **decide which operations in the TrfP(s) will be performed by technical systems, TS, alone or in mutual cooperation with other operators; and which TS(s) (or parts of them) need to be designed**;

Transformation process see **figure 2**.

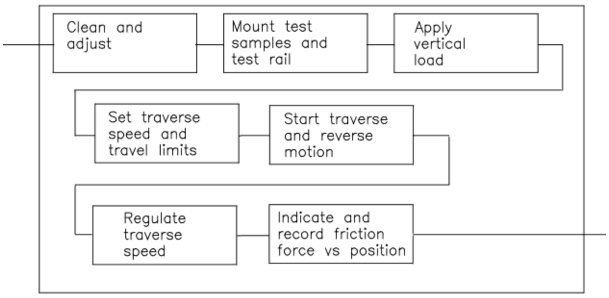


Fig. 2 Friction Equipment – Transformation Process

(P3.1.3) **establish a technology (structure, with alternatives) for that transformation operation, and therefore the effects (as outputs) needed from the technical system**;

Available technology see **figure 3**.

(P3b) **establish what the technical system needs to be able to do (its internal and cross-boundary functions, with alternatives);**

The TS-function structure developed for this project is shown in **figure 4**. Most of these TS-functions are solvable by routine means, in this case the author has chosen to number all TS-functions.

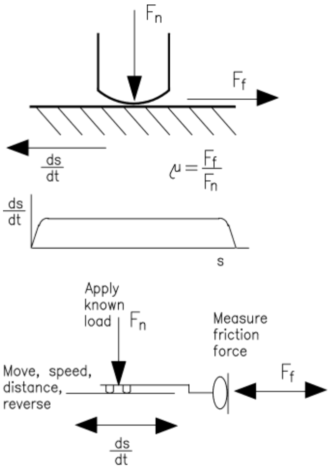


Fig. 3 Friction Equipment – Technology

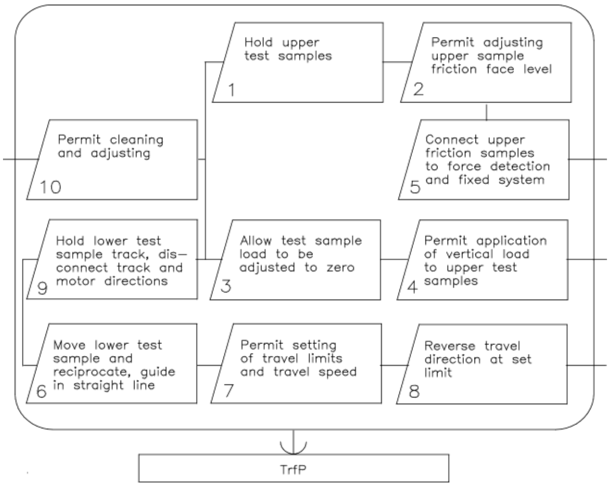


Fig. 4 Friction Equipment – Function Structure

(P4) **establish what organs (function-carriers in principle and their structure, with alternatives) can perform these functions**;

Figure 5 shows a morphological matrix, with alternative solution proposals where available. **Figure 6** shows the TS-organ structure, with alternatives. The structure selected for the lower section can be attached as show, or mirrored 180°. Two alternatives for the base section are shown, the actual choice can be anywhere between these extremes, arrangement C was chosen.

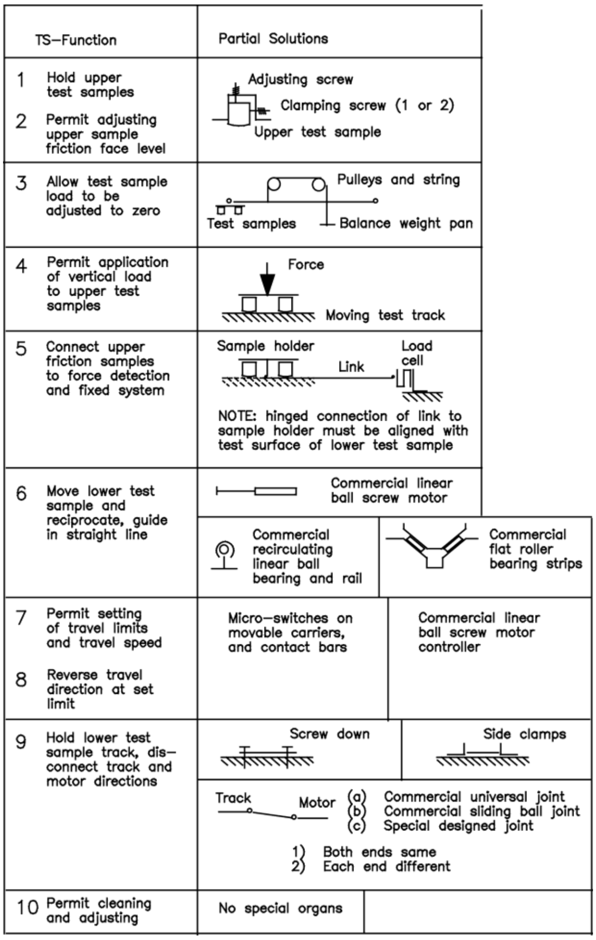
** embodying/laying out and detailing*:

(P5a) **establish what constructional parts and their arrangement are needed, in sketch-outline, in rough layout, with alternatives**;

(P5b) **establish what constructional parts are needed, in dimensional-definitive layout, with alternatives**;

(P6) **establish what constructional parts are needed, in detail/assembly drawings, with alternatives**.

Sample layout and detail drawings (pencil on paper) are shown in **figure 7**. In this case, because these drawings are unlikely to be reused, pencil-on-paper was considered adequate. After a first trial, a modification was found necessary – this layout shows the changes.



TS–Function	Partial Solutions	
1 Hold upper test samples 2 Permit adjusting upper sample friction face level	Adjusting screw Clamping screw (1 or 2) Upper test sample	
3 Allow test sample load to be adjusted to zero	Pulleys and string Test samples Balance weight pan	
4 Permit application of vertical load to upper test samples	Force Moving test track	
5 Connect upper friction samples to force detection and fixed system	Sample holder Link Load cell NOTE: hinged connection of link to sample holder must be aligned with test surface of lower test sample	
6 Move lower test sample and reciprocate, guide in straight line	Commercial linear ball screw motor	
	Commercial recirculating linear ball bearing and rail	Commercial flat roller bearing strips
7 Permit setting of travel limits and travel speed 8 Reverse travel direction at set limit	Micro–switches on movable carriers, and contact bars	Commercial linear ball screw motor controller
9 Hold lower test sample track, dis–connect track and motor directions	Screw down	Side clamps
	Track Motor (a) Commercial universal joint (b) Commercial sliding ball joint (c) Special designed joint 1) Both ends same 2) Each end different	
10 Permit cleaning and adjusting	No special organs	

Fig. 5 Friction Equipment – Morphological Matrix

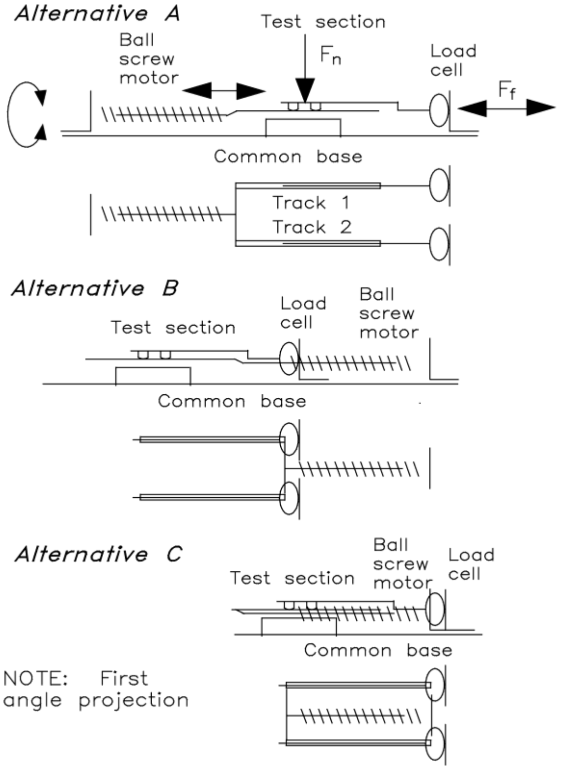


Fig. 6 Friction Equipment – Organ Structure

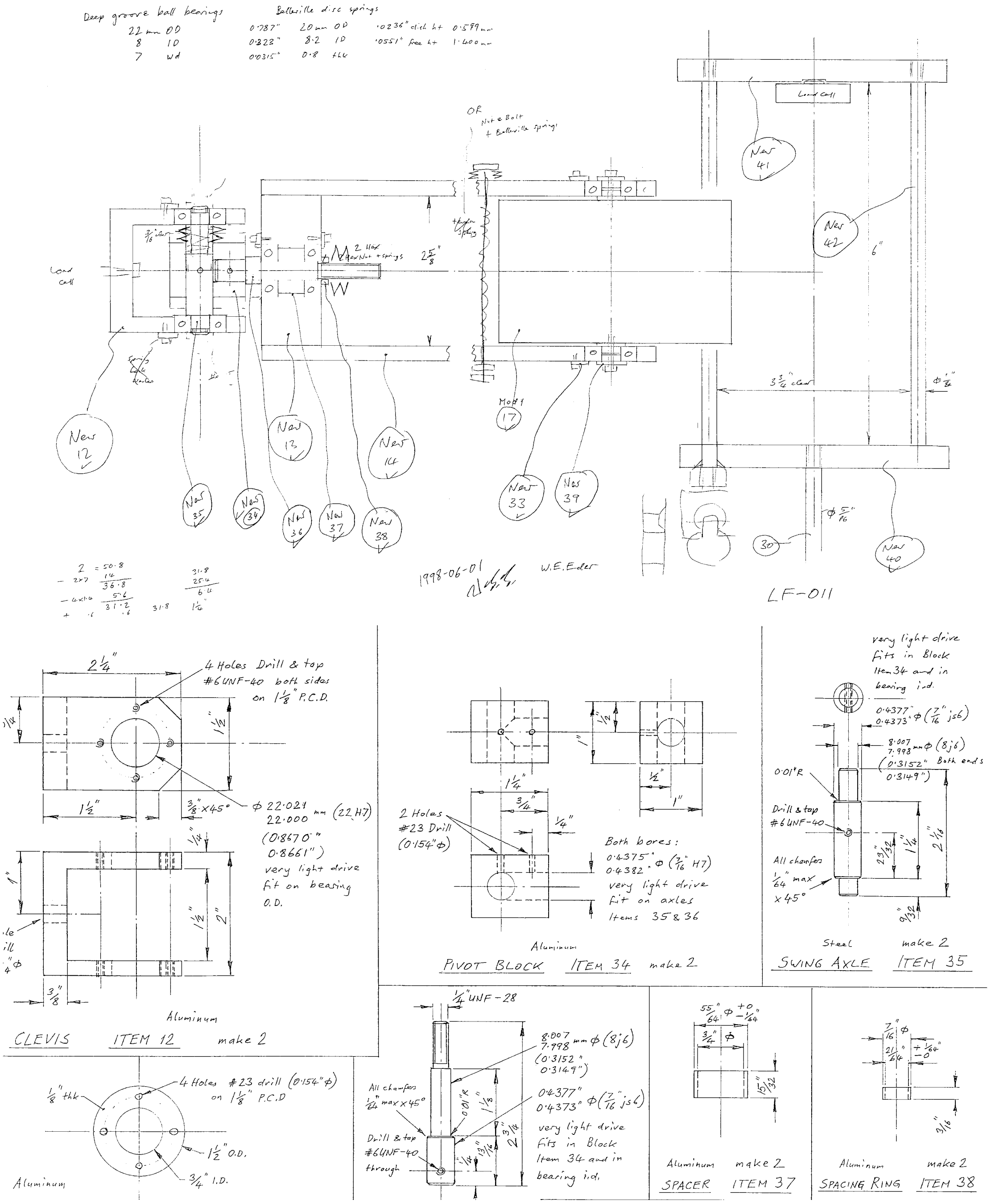


Fig. 7 Friction Equipment – Layout and Detail

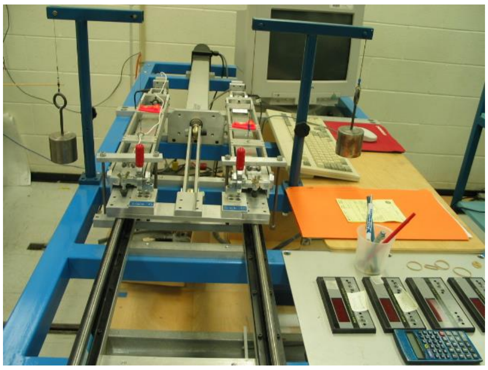


Fig. 8 Friction Equipment – Operational

3 Closure

The friction test equipment, **figure 8**, has been in successful operation, and has contributed well to the research program. The prescribed length of paper does not allow a fuller discussion of the recommended method, but see [1,2]. An experienced engineering designer working below his/her limit of expertise [3] will be able to reach a similar result whilst neglecting some of the earlier formal steps and models. As soon as this limit of expertise is reached, the earlier steps deliver valuable support in understanding and organizing the information to help solve the design problem. These steps do not guarantee a solution, but they assist the engineering designer.

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