CONTROL SYSTEMS ANALYSIS & DESIGN SERVER

F. Morilla*, A. Fernández[+], S. Dormido Canto*

** Dpto de Informática y Automática, UNED, Avda. Senda del Rey 9, 28040 Madrid, Spain. Phone:34-91-3987156, Fax:34-91-3986697, E-mail: fmorilla@dia.uned.es; sebas@dia.uned.es*

[+] Instituto de Automática, Facultad de Ingeniería, Universidad de San Juan, Avda. Libertador General San Martín 1109 Oeste, 5400 San Juan, Argentina. E-mail: arnoldo@inaut.unsj.edu.ar; afernandez@dia.uned.es

Abstract: This paper describes an implementation of the tool *SISTEMAS* in order to use as WWW Server for analysis and design of control systems. It can be used via an Intranet or Internet, alone or integrated in the virtual and remote control laboratory. This laboratory is being developed in the Informática y Automática Department of UNED. The tool covers widely the key concepts of Automática I (an annual course of feedback automatic control). It has been used since the academic year 94/95 as support material in the subject and in one of the practical sessions that take place in the laboratories of the Facultad de Ciencias (Sciences Faculty) of UNED. With the new idea of WWW service, the student could be able to use the tool as many times as he needs (to study or to take a practical session) from his house or from his Associated Centre; he will need only an Internet connection.

Keywords: Compensation, computer-aided control system design, laboratory education, distance learning.

1. INTRODUCTION

Since 1994 the Informática y Automática Department of UNED has a CACSD (Computer-Aided Control Systems Design) tool that makes easier the design of linear feedback control systems in Matlab-Simulink (Dormido Canto, 1994; Morilla, *et al*., 1994; Morilla, *et al*., 1995). The tool covers widely the key concepts of Automática I (an annual course of feedback automatic control) and since academic year 94/95 has been used with the name *SISTEMAS*, with successfulness between the students (approximately 70 students per year), in one of the practical session of the subject (Dormido Canto, *et al*., 2001). In the same course, it was removed its dependence of Simulink and it was made an implementation for the student version of Matlab 4.0 in order to use it in the students's home, previous request to the teaching team. Since the academic year 99/00 the tool is included as support material in the CD-ROM edited with the guidebook course of the Facultad de Ciencias of UNED.

Since 1999, the Department is working in the project of news virtual an remote laboratories for the distance learning of automatic control, whose results has been presented in (Dormido, *et al*., 2000; Sánchez, *et al*., 2000). Since 2001 the project has a little financing for next three years within the Research's Promotion Plan of the UNED 2000.

This paper describes an implementation of the tool *SISTEMAS* in order to use as WWW Server for analysis and design of control systems. It can be used via an Intranet or Internet, within the new concept CSADS (Control Systems Analysis & Design Servers), alone or integrated in the virtual and remote control laboratory of the Informática y Automática Department. To implement the tool in Matlab Web Server have been necessary significants changes in the *.m files and a full development of the new interface, based on dynamic HTML pages. But also its functionality has been increased in order to report the designs and to make easy the evaluation of the practical sessions. 50 students have used the server this academic year via the Intranet of the Facultad de Ciencias (Science Faculty) of UNED, but also some students and the teaching team have tested it from their houses.

A overview of the *SISTEMAS*'s features is shown in section 2. The characteristics of the Web version of *SISTEMAS* are described in section 3. Where also is mentioned the usual sequence of a practical session.

Finally the paper is completed with the conclusions in section 4.

2. FEATURES OF "*SISTEMAS*"

Given a process model and established the control system specifications, the *SISTEMAS* tool is able to advise about the compensator type and to find the analytical solution. *SISTEMAS* uses the design methodology summarised in section 2.1, described with more detail in (Dormido Canto, 1994; Morilla, *et al*., 1994). The following general features delimit the scope of the tool:

- The control system can be analog (continuous-time), discrete (discrete-time) or digital (sampled-data), with unity feedback gain, as it is shown in Figure 1.
- The process model and the controller are described by their transfer functions. Both transfer functions are continuous when the control system is continuous and discretes when the control system is discrete-time. But if the control system is digital, the process transfer function will be continuous and the controller transfer function will be discrete.
- The control system specifications combine steady-state accuracy (steady-state errors for unit step and for unit ramp) and the relative stability (phase margin and gain margin).
- The compensator to design can be: a PID controller or its alternatives (PI, PD), a lead network (LEAD) or a lag network (LAG). This is shown in Table 1.

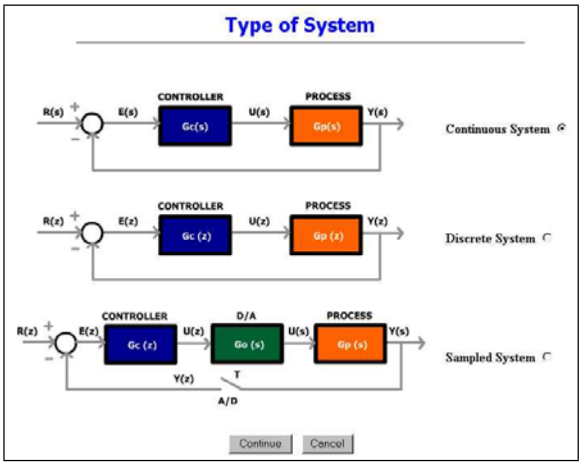

Fig. 1. Control systems considered in *SISTEMAS*.

The tool also allows to analyse the control system, with a view to the subsequent design or to check the latest design. The analysis comprises: the step response (of the process, of the control system), the open-loop frequency response (Bode and Nyquist plots) and the root locus. Therefore, the stability and the main features of the design are studied. An example is illustrated in Figure 2.

Table 1: Continuous and discrete transfer functions of the compensators

Lead-lag network	PID controller
$K\dfrac{\frac{s}{\omega_{s_o}}+1}{\frac{s}{\omega_{s_p}}+1}$	$K_P\left(1+\dfrac{1}{T_I\, s}+T_D\, s\right)$
$K\dfrac{\omega_{z_o}\left(1+\omega_{z_p}\right)}{\omega_{z_p}\left(1+\omega_{z_o}\right)}\dfrac{\frac{z}{\omega_{z_o}}+1}{\frac{z}{\omega_{z_p}}+1}$	$K_P\left(1+\dfrac{T}{2T_I}\dfrac{z+1}{z-1}+\dfrac{2T_D}{T}\dfrac{z-1}{z+1}\right)$

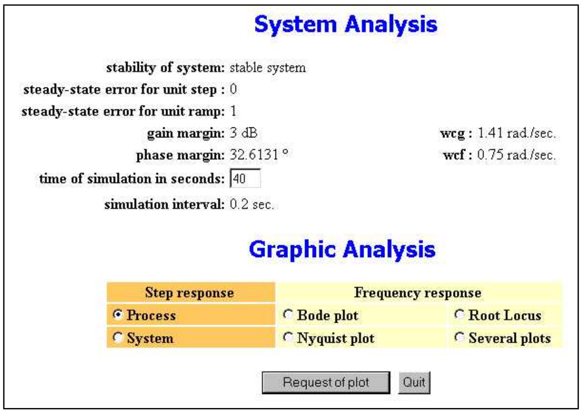

Fig. 2. An example of analysis.

2.1 Design with "SISTEMAS".

Any control system must be stable, and so the stability is one of the main specifications in the control system design. In addition to the absolute stability, a control system must have an adequate relative stability; that is to say, the transient system response must be relatively fast and with small overshoot. The control system must also gets good tracking accuracy. The relative stability and the steady-state accuracy are sometimes incompatible specifications; hence a trade-off is needed between these conflicting requirements.

The *SISTEMAS* tool approaches the automatic control system design in two steps:

1º) *Steady-state error compensation*: as the procedure that, given a process and the steady-state specifications, selects the set of possible compensators and determines the value of some control parameters.

2º) *Compensation by phase margin*: as the procedure, next to the steady-state error compensation, that selects the more adequate compensator and determines the remainder of control parameters in order to get the specified phase margin (PM) (Phillips and Harbor, 1991; Saadat, 1993). The compensator selection is sometimes conditioned by the specified gain margin (GM).

Table 2 shows all possible cases of steady-state compensation with the compensators considered in *SISTEMAS*, they are grouped in two families, (LEAD, LAG, PD) and (PI, PID), because:

- The lead-lag network and the PD controller allow to modify the finite error of the uncompensated control system selecting appropriately one of its parameters, the dc gain K or the proportional gain K_P respectively.
- The PI and PID controllers allow cancel the finite error of the uncompensated system, and its integral gain $K_I=K_P/T_I$ can be used to get a finite and nonzero steady-state error of upper degree.

Table 2: Possible compensators for the steady-state error compensation

uncompensated system		**compensated system**		**possible compensators**
error for a unit step	error for a unit ramp	error for a unit step	error for a unit ramp	
finite and nonzero	unbounded	finite and nonzero	unbounded	LEAD,LAG,PD
finite and nonzero	unbounded	zero	finite and nonzero	PI, PID
zero	finite and nonzero	zero	finite and nonzero	LEAD,LAG,PD
zero	finite and nonzero	zero	zero	PID, PID
zero	zero	zero	zero	LEAD,LAG,PD PI, PID

In Table 3 the compensation formulas by phase margin for continuous control systems are shown, they were proposed by Phillips and Harbor (1991) and can also be used for discrete and digital control systems in the bilinear transformation domain. G(jω) is the frequency response of the process and θ is the angle that the compensator must contribute in order to get the desired phase margin $PM_{desired}$ at the frequency ω_c. Its value is given by

$$\theta = PM_{desired} - 180^o - \arg(G(j\omega_c)) \quad (1)$$

To use the formula of Table 3 it is necessary to have the frequency design ω_c selected and without any restrictions to the control parameters (K, ω_{so} y ω_{sp} in lead-lag network case; K_P, $K_I=K_P/T_I$ and $K_D=K_PT_D$ in PID controller case). But this is not the usual situation in *SISTEMAS*, because ω_c is still unknown and also because previously, as consequence of the steady-state compensation, the K parameter of the lead-lag network, the K_P parameter of the PD controller or the K_I parameter of the PI or PID controllers has been determined, but the compensator is still unselected. Therefore the compensation by phase margin in *SISTEMAS* includes also the selection of the compensator, one between the members of the family (LEAD, LAG, PD) or (PI, PID), and the determination of the frequency range for ω_c (Saadat, 1993). Leaving as degree of freedom the selection of the design frequency, joined with another degree of freedom (the selection of the integral gain or the derivative gain) when the compensator is PID and its integral gain is not determined by the steady-state compensation.

Table 3: Compensation by phase margin

Lead-lag network	PID controller
$\omega_{s_o} = \dfrac{\mathrm{sen}\theta}{\dfrac{1}{\lvert K\,G(j\omega_c)\rvert} - \cos\theta}\,\omega_c$	$K_P = \dfrac{\cos\theta}{\lvert G(j\omega_c)\rvert}$
$\omega_{s_p} = \dfrac{\mathrm{sen}\theta}{\cos\theta - \lvert K\,G(j\omega_c)\rvert}\,\omega_c$	$K_D\,\omega_c - \dfrac{K_I}{\omega_c} = \dfrac{\mathrm{sen}\theta}{\lvert G(j\omega_c)\rvert}$

2.2 Types of design.

SISTEMAS offers three types of design. They differ in the degrees of freedom allowed the user. In AUTOMATIC DESIGN, the user don't has degrees of freedom, the selection of the controller and the selection of the design frequency are made by the application. In MANUAL DESIGN, the user could be able to choose the compensator (one of the controllers that can compensate the steady-state errors), the design frequency (inside the frequency range of possible solutions) and the integral gain or the derivative gain if it would be necessary.

The AIDED DESIGN is an intermediate choice, where the user chooses the design frequency and the application selects the controller with the following criteria:

- PI or PID: just when the PM of the uncompensated system is less than the PM desired, the PID controller is selected.
- (LEAD, PD) or LAG: just when the PM of the uncompensated system is bigger than the PM desired, the LAG network is selected.
- LEAD or PD: just when the GM of the uncompensated system is less than the GM desired, the PD controller is selected.

SISTEMAS includes the following rules in order to select automatically the design frequency:

- LEAD, LAG, and PD without condition on K_P, PI or PID without condition on K_I: ω_c is selected as the geometrical mean of the frequency range extremes.
- PI with condition on K_I: ω_c is selected as the maximum value of the frequency range that verifies also the equation:
$$K_I\,\lvert G(j\omega_c)\rvert + \omega_c \mathrm{sen}\theta = 0 \quad (2)$$
- PD with condition on K_P: ω_c is selected as the minimum value of the frequency range that verifies also the equation:
$$K_P\,\lvert G(j\omega_c)\rvert - \cos\theta = 0 \quad (3)$$

- PID with condition on K_I: ω_c is selected as the minimum value of the frequency range that verifies also the equation:

$$0 < \left(\frac{K_I}{\omega_c} + \frac{\mathrm{sen}\theta}{|G(j\omega_c)|} \right) \omega_c < K_I \qquad (4)$$

It includes also the following rules in order to select automatically the integral or derivative gain when the compensator is PID without condition on K_I:

- If $\theta<0$: K_I is selected as 20% upper the minimum possible, to be exact

$$K_I = -1.2 \frac{\mathrm{sen}\theta}{|G(j\omega_c)|} \omega_c \qquad (5)$$

- If $\theta>0$: K_D is selected as 20% upper the minimum possible, to be exact

$$K_D = 1.2 \frac{\mathrm{sen}\theta}{\omega_c\, |G(j\omega_c)|} \qquad (6)$$

3. THE WEB VERSION OF "*SISTEMAS*"

The main objective of *SISTEMAS* project in 1994 (Morilla, *et al*., 1994) was to develop a tool in Matlab for that beginning students in feedback control (students of Automática I) could be able to analyse and design linear control system without have need of programming in Matlab, and only being enough with a minimum knowledge of its syntax. Nevertheless the user will need to have a Matlab version (the student fourth edition or upper).

Since then the tool has experimented several small changes, mentioned in section 1, and nowadays there is an implementation on version 5.3 of Matlab. However this work describes the most important change of *SISTEMAS*. This change is because of that the Informática y Automática Department shows a constant concern to give a control teaching of quality and fitted to the new technological challenges.

So, the Web version of *SISTEMAS* presents another advantages in relation to the local version:

- The users will not need to have Matlab. They only need a standard and user-friendly browser.
- The teaching team of Automática I can schedule some practices that the students can make from their houses whenever and how they want, without timetable.
- Only there is a working copy of the tool, which is in the server of the Department. So, its maintenance and improvement can be almost continuous without disturb the users. At the same time is very easy to have a control on the access.

The new version of *SISTEMAS* has all the original functionality, where only the interface has been changed to dynamic HTML pages. But it also includes new functionality in order to make easy to the teacher the evaluation of the student's designs. One of the most representative HTML pages of *SISTEMAS* is the Work Station page, see Figure 3, that shows the diagram of the control system (analog, discrete or digital) selected in that moment and offers the following six options:

Type of system: With this option the user will access to the page of Figure 1, where he could be able to change the control system.

Configuration: This option allows the user access to the HTML page where he can check and change the transfer functions of the process and the controller, and the sample time when the control system is discrete or sampling.

Analysis: This option presents some features of the control system (stability, steady-state errors, phase margin and gain margin), an example is shown in Figure 2, leaving to the user another options of analysis (step response, frequency response and root locus). Besides the user has an option to request a more complete analysis, where he will be able to see the step response, the Bode plot and the root locus in the same HTML page.

Design: This option provides information about the steady-state errors of the uncompensated system and of the current control system. Allowing the user: request a new design (with the same or different specifications), select the type of design or return to the Work Station. See as example the Figure 4.

Report: This option allows the user to document his designs.

Exit: to quit the program.

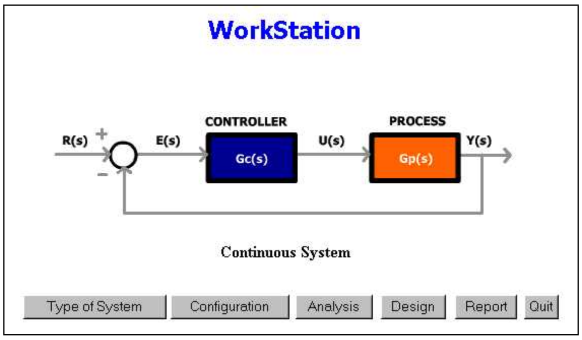

Fig. 3. A snapshot of the Work Station when an analog system is selected.

Another representative page HTML of *SISTEMAS* is the Designed Controller, see Figure 5, where as consequence of the design, the user receives information about the controller transfer function, its parameters and an automatic justification of how the solution has been reached. He can return later to the Design page for test if the specifications have been achieved, but also he has the option of make a comparative analysis between the uncompensated system and the compensated system.

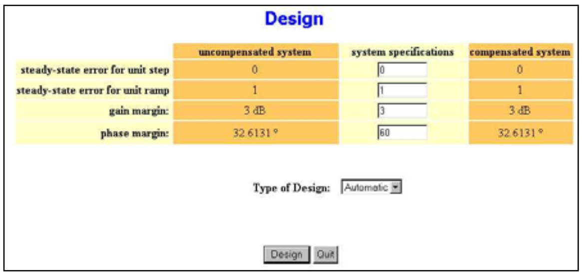

Fig. 4. A snapshot of Design page after to make a manual design.

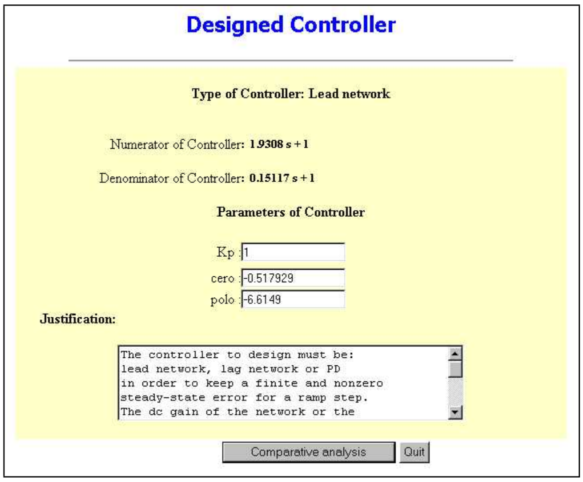

Fig. 5. A snapshot of the Designed Controller page.

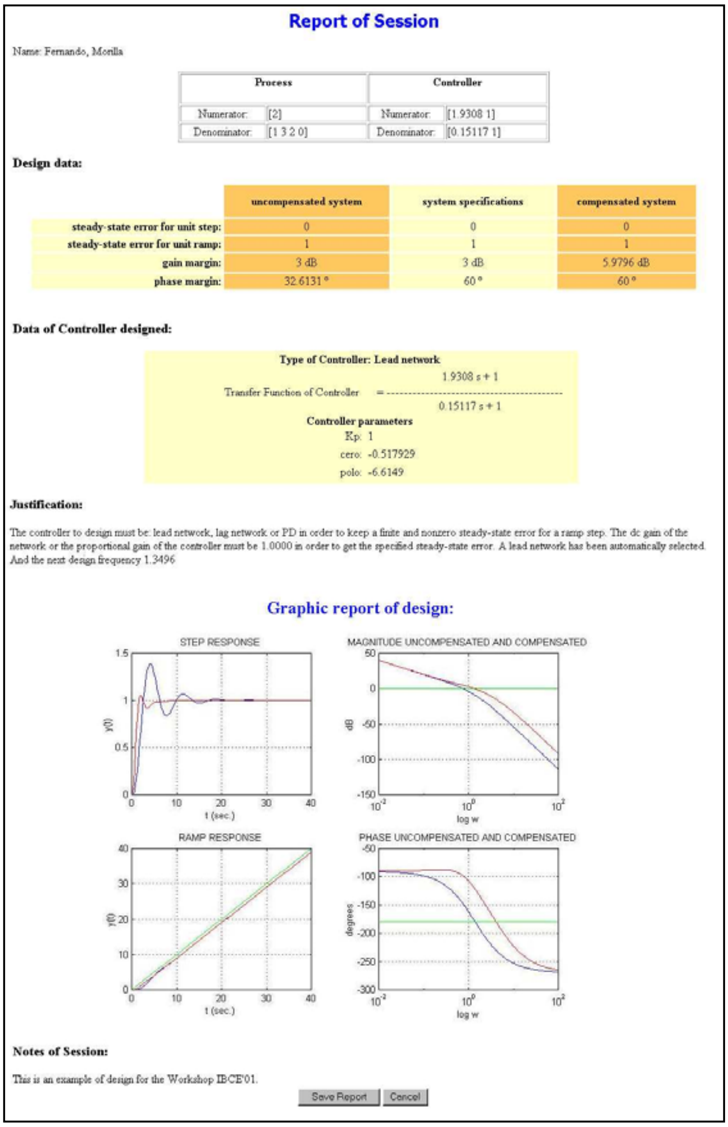

Fig. 6. Example of report generated by *SISTEMAS*

In Figure 6 an example of a report generated by *SISTEMAS* is shown: it consists of a HTML page with outstanding information of the last design, the name of the user and a field with the comments that the user had wanted include. The user has then the option of print the report from the browser, but also he has the option of save the associate information of the report in his computer. These types of reports have as aim that the student can document the designs of a practical session. But in addition, if the student have been concerned about to save one report by each design, the teacher could check and evaluate them using the part of *SISTEMAS* developed with this purpose, the teacher only needs to know the user code assigned to each design.

3.1 Practical session.

The Web version of *SISTEMAS* is ready for use in spanish or english language. Next the usual sequence of a practical session with it is described:

Starting the session: The user access to the way in HTML page of the server, see Figure 7, where after to select the language he can start a session or retrieves a session that he had suspended by some reason. The last one is possible because all session in *SISTEMAS* has associated a user code.

Selection, configuration, analysis and design of the control system: The user access to the Work Station page of Figure 3, where he can unchain all the tasks aimed at the design of the compensator.

Reporting the design: From the Work Station page the user must generate the session report when he thinks over that the current design is the most suitable to the aims of the practical session.

Quiting the session: The user goes away from *SISTEMAS* and notes down the user code just in case he decides retrieve the session in another time.

Fig. 7. The way in page of *SISTEMAS*.

4. CONCLUSIONS

The countless examples of design made by de students and by the teaching team of Automatica I with *SISTEMAS* prove the great utility of this type of tool for teaching aims. With the version presented in this work, its utility is extended even more because:

- It is not mandatory that the users have Matlab in their computers.
- The new interface is more user-friendly for anyone that had used sometime a standard Web browser.
- The user could access at any moment and from anywhere to the last version of the tool (the only one, really available).
- The teaching team will have more flexibility to schedule a set of practical sessions, as well as for its pursuing and evaluation.
- The Informática y Automática Department of UNED can integrate it as another pillar of the virtual and remote laboratory of Automatic Control, allowing the access to the students of another subjects and of another universities.
- The maintenance and improvement of the tool can be almost continuous without disturb the users.

ACKNOWLEDGEMENTS

The authors wish to acknowledge to the Universidad Nacional de San Juan (Argentina) and to the UNED by allow and finance the stay of lecturer A.W. Fernández in the Informática y Automática Department.

REFERENCES

Dormido Canto, S. (1994). Proyecto de diseño y ajuste de controladores en el entorno Simulink. Escuela Técnica Superior de Ingenieros Industriales, I.C.A.I., Mayo.

Dormido, S., J. Sánchez, and F. Morilla (2000). Laboratorios virtuales y remotos para la práctica a distancia de la Automática. Sesión Plenaria, XXI Jornadas de Automática. Sevilla 18, 19 y 20 de septiembre.

Dormido Canto, R., S. Dormido Canto, N. Duro, R. Hernández, J.C. Lázaro, I. López, F. Morilla (Coordinador), R. Pastor, A. Pérez de Madrid, S. Ros and F. Vázquez (2001). Guiones de Prácticas de la asignatura: Automática I. Revisión 2001. Dpto. de Informática y Automática, UNED.

Morilla, F., S. Dormido Canto and S. Dormido (1994). Diseño de Controladores en el entorno MATLAB-SIMULINK. Jornadas de Automática, Málaga.

Morilla, F., S. Dormido Canto and S. Dormido (1995). Herramienta para el análisis y diseño en el entorno Matlab-Simulink. MATLAB'95 I Congreso de Usuarios de Matlab, Madrid.

Phillips, C. L. and R.D. Harbor (1991). Feedback Control Systems, Second Edition. Prentice-Hall International, Inc.

Saadat, H. (1993). Computational Aids in Control Systems Using MATLAB. McGraw-Hill International Editions, Electrical Engineering Series.

Sánchez, J., F. Morilla, S. Dormido, J. Aranda and P. Ruipérez (2000). Conceptual Learning of Control by Java-based Simulations. IFAC/IEEE Symposium on Advances in Control Education (ACE 2000), 17-19 December, Gold Coast, Australia.